High Frequency Modelling of Powerline Distribution Networks.

Thesis

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High Frequency Modelling of Powerline Distribution Networks

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Abstract

The purpose of this thesis is to investigate the available bandwidth for communications on electricity distribution networks. The work is concentrated on the low voltage parts of the network to maximise the use of that bandwidth and to model parts of the distribution system in order that the characteristics can be theoretically examined before practical on site investigation takes place.

The work begins by looking at the history of the subject, past and currently available systems, their methods of operation and their limitations.

The work continues by developing transmission line equations and transmission line parameters, for both single and multi phase, showing the implementation of these equations for power cables and distribution networks.

A comprehensive study of the topology and structure of the UK electricity distribution network is given in order to provide an understanding of the basic network elements which are interconnected to form a pervasive nationwide electricity transmission and distribution network.

The research concentrates on the low voltage electricity distribution network as this is, in communication terms, the most cost sensitive area providing an alternative established local access infrastructure. However an overview of the whole UK electricity transmission and distribution network architecture is included, as this is thought to be a necessary part of understanding the composite system and the associated problems of overlaying cost effective telecommunication services.

Software listings are included in the appendices and an explanation of the mathematics and programming is included in chapters 3 and 7.

The initial investigations showed that low voltage distribution networks were noisy and that the noise levels varied with time. These initial investigations also showed that power levels in the order of milliwatts would allow communications during low noise periods. This led to the development of the mains filter to prevent noise from customers' premises from entering the network. Fitting of these filters fixed the noise levels on the network and allowed the low power signals to be used.

After the filters are fitted to a network the parameters affecting the characteristics of that network are much simplified and fixed, providing no physical alterations take place. Because of this "fixing of the response" a computer analysis was thought to be an option that would allow the characteristics of any network to be calculated prior to practical installation. This has been done and the results are given in this thesis.

Memorandum

All work and ideas recorded in this dissertation are original unless otherwise acknowledged in the text or by reference. The work has not been submitted in support of an application for another degree in this university, nor for any degree or diploma at any other institution.

Whilst the author has undertaken a study of the UK electricity distribution architecture it should be noted that the information provided from the study is given to support and place in context his core work and is not intended to be an exhaustive or definitive study of the UK electricity distribution architecture.

Acknowledgements

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This thesis is dedicated to the author's wife, Ann and his two children, Elizabeth and Christopher who have supported, in every possible way, all the work undertaken in the four years leading to the submission of this thesis.

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Glossary

BOT	Board of trade unit = 1 kwh
REC	Regional electricity company
CEGB	Central electricity generating board
VLF	Very low frequency
HF	High frequency
VLSI	Very large scale integration
LV	Low voltage
MV	Medium voltage
HV	High voltage
ESI	Electricity supply industry
PSTN	Public switched telephone network
TEM	Transverse electromagnetic
E	Electric field
H	Magnetic field
CNE	Combined neutral earth
XLPE	Cross linked poly-ethylene
PVC	Poly vinyl chloride
VSWR	Voltage standing wave ratio
TX	Transmit / Transmitter
RX	Receive / Receiver
NFM	Narrowband frequency modulation
SSBSC	Single sideband suppressed carrier
AM	Amplitude modulation
FM	Frequency modulation
OFDM	Orthogonal frequency division multiplexing
HRC	High Rupture Capacity
DECT	Digital Cordless Telephony Standard
CT2	Cordless Telephone 2 Standard

Chapter 1. The Electricity Supply Industry

1.1 Introduction

Reliable powerline communications has been the subject of significant research going back some 70 years. It is generally thought that reliable communications with high data rates cannot be achieved because of the dynamic unpredictable nature of the power lines and the extreme noise levels and attenuation. The nature of this noise is predominately impulsive and man-made. The unpredictability of the network is such that a system can be working but can cease to work at any time. The cause may be any change in the characteristics of the network such as switching on or off any appliance connected to the network. To minimise the effect of these changes, systems have tended to use low frequency signalling coupled with very secure packeting of the data, resulting in low data rates.

The difficulties described apply to all attempts for communication on power lines. In the case of overhead supplies, ring mains and most internal wiring, these limitations must be endured. In the case of underground supplies there are various methods of minimising their cause and effect.

The research programme described, investigates work done in examining the low voltage power distribution network as a means for transmitting signals in the frequency range 1 MHz to 10 MHz. Background searches revealed no documented research in this area as it was thought that attenuation along the cables at these frequencies would be prohibitive to communications and that the environment was far too noisy to support communications without employing prohibitive power transmission levels resulting in excessive radiation of the transmitted signals [Ref. 2].

1.2 Electricity supply Industry (ESI)

In 1831 Michael Faraday discovered the principal of converting mechanical energy into electrical energy. In 1856 a practical use for this discovery was found when a lighthouse was fitted with carbon arc lamps. Between 1856 and 1879 several exhibitions had displayed the use of arc lamps and several private sites were commissioned for their installation. The first private house installation being at Porchester Gardens where a battery of Grove cells was used to power small arc lamps. In 1879, Thomas Alva Edison invented the incandescent lamp using platinum wire and carbonised filaments derived from bamboo. At the same time Mawson and Swan of Newcastle, invented an incandescent lamp using cellulose filaments produced by immersing cotton threads in sulphuric acid. These threads were enclosed in evacuated glass envelopes to prevent oxidisation. In 1880 there was an exhibition of gas lighting in Glasgow and the first demonstration of incandescent electric lighting was displayed. This demonstration won a medal for "supplying power for lamps" from the Glasgow Philosophical Society [Ref. 1].

This exhibition produced orders for the installation of electric lighting at the Glasgow post office and the North British Railway goods yard, followed by the wiring of King's Cross Station for the Great Northern Railway. Later in 1880 a portable generating set was installed at Alexandra Palace under the supervision of a Mr. Sidney Baynes who was helped by a young Mr. Ferranti. This was the start of Mr. Ferranti's interest in electrical engineering. Towards the end of 1880 a demonstration at the collieries of the Stanton Ironworks Company proved, to the satisfaction of the Mining Commissioners to collieries, that electric incandescent lighting could be used safely all the way to the working face.

The first example of house lighting by incandescent lamp was performed by Cromptons at Berechurch Hall near Romford for Mr. Jesser Coupe of Ind, Coope and company in 1881 [Ref. 1].

The International Exposition of Electric Lighting was held in Paris during the summer and autumn of 1881. It was at this exhibition that standard terminology for electrical units was laid down. The terms ampere, volt, watt and ohm were all defined and their method of measurement fixed. At the same time as the Paris exhibition, a generator at the Gare du Nord in Paris supplied power to the repair shops of the Northern Railway at Creil some twenty miles away.

Electrical wiring of small sites continued but an act of parliament passed in 1882 limited the tenure of electrical undertaking to twenty-one years. This effectively stopped the investment necessary for the development of a large electrical distribution network in England, though in 1883 in London the Edison Company installed steam powered generators in a disused house to supply houses in the Holborn Viaduct area with street lights. The act of 1882 was repealed in 1886 and the installation of small areas of distribution began to form the component parts required for a large scale distribution network. During this time the cost of using electricity was between £1 per annum for a 10 amp meter to £1 16s for a 150 amp meter, with electricity costing 8d per B.O.T. [1 Board of Trade Unit (BOT) = 1kWh].

The City and South London Railway was opened in 1890. This was the first time exclusive use had been made of electric locomotives. The whole of the underground network was converted to electricity and the electrification of many suburban lines followed. In 1932 there were 650 miles of electrified railway lines [Ref. 1].

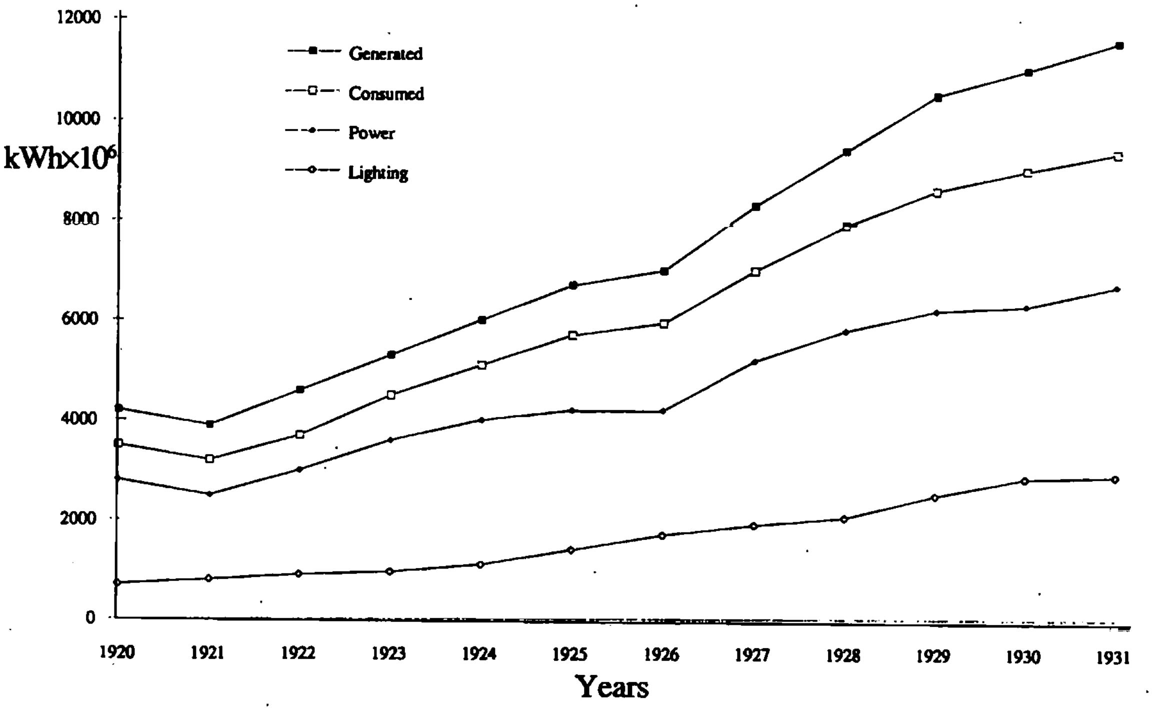

Figure 1.1. Power generation and consumption in million kilowatt hours, 1920-1931

In 1906 the United Kingdom had a generating capacity of 1 million kilowatts and sold over 500 million units of electricity. In 1926, 476 generating stations had a generating capacity of 4.5 million kilowatts. This trend for growth is shown in figure 1.1.

This growth continued for thirty years before any attempt was made to consolidate the supply of electricity. In 1916 proposals were made to link individual power stations in Britain to form a national grid. In 1926 the Central Electricity Board was established, followed by the construction of the national grid between 1928 and 1938 which led to the nationalisation of electricity supply in 1948. Figure 1.1 shows the increase in electricity usage from the period 1920 to 1931.

The industry was split into three tiers:

(i) The Electricity Council; responsible for raising capital, setting tariff and advising the Government.

(ii) The Central Electricity Generating Board; responsible for generating electricity and distributing to the area boards.

(iii) The twelve area boards; responsible for overseeing the supply of electricity to customers (England and Wales only).

From 1948 to 1965 the growth rate in the supply was 8.4% per annum [Ref. 3]. In 1965 this growth rate came into line with the economic output of the country.

The electricity supply industry remained unchanged until the 1989 electricity act led to the privatisation of the industry [Ref. 3]. At this time each of the twelve area boards became a private company and the C.E.G.B. was split to form Powergen and National Power (fossil fuels), Nuclear Electric (Government owned) and several other smaller generators. The National Grid Company, jointly owned by the twelve regional electricity companies (RECs), owns the high voltage distribution network for the mass distribution of electricity. The Office of Electricity Regulation replaced the electricity council and stands over the generating and distribution companies to see fair play. Each REC supplies electricity to customers within its own geographical area. From the date of privatisation customers requiring over 1 MW have been able to source their supply from any of the RECs. This 1 MW limit was reduced in 1994 to 100 kW and it is proposed that it should be removed completely in 1998 allowing all customers their choice of supplier.

1.3 Distribution methods

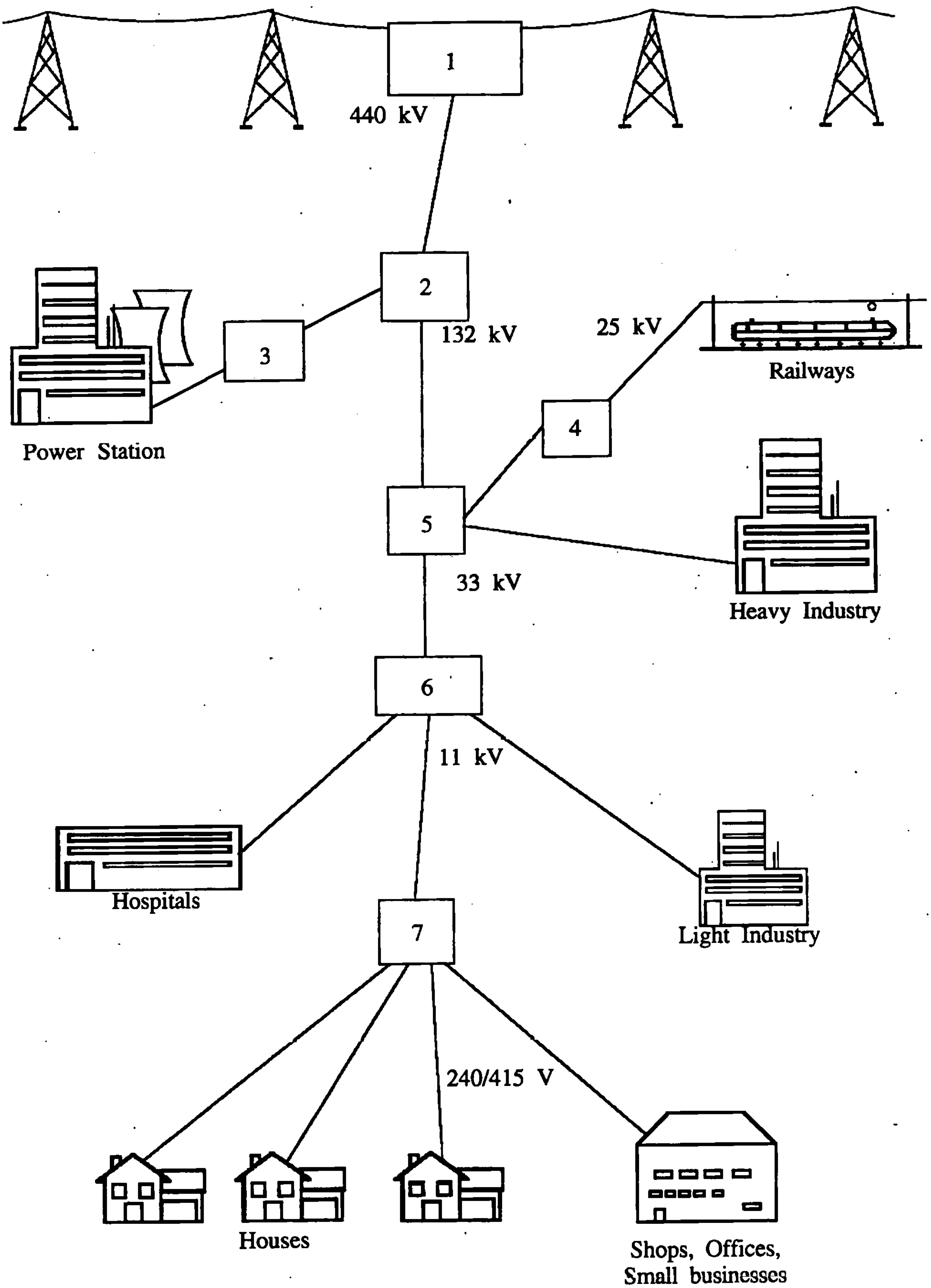

Figure 1.2. Electricity Distribution Network

Figure 1.2 shows the distribution format for each of the RECs in schematic form. The voltages given in the schematic are not the only voltages used but, because of the drive to standardise supply, in most cases where different voltages are present there use is being discontinued as and when the need for maintainance arises. The following is an explanation of the distribution methods for each part of the network, these are numbered in figure 1.2. This topic is discussed in more detail in chapter 5.

1) The backbone of the National Grid. Supply voltages in excess of 275 kV. All of the distribution at this voltage is via overhead cables flown between steel pylons.

2) The voltage is reduced to 132 kV. Some power stations may generate at this voltage. Distribution is normally via overhead cables but short runs within substation areas can be underground.

3) Grid in feed. Power stations will normally generate at 25 kV, this voltage is matched to the nearest suitable supply point via a grid in feed transformer. The distance to this transformer is kept to a minimum in order to minimise losses. This matching method applies to all generating methods.

4) Supply for the railways at 25 kV for electrified railway lines. The 25 kV feed is supplied to the railways and is distributed to the overhead supply rails by the railway company. The transformers for this distribution are owned by the REC.

5) The voltage is reduced to 33 kV. This voltage is supplied direct to heavy industry or is distributed for further reduction. Supplies can be either overhead or underground. The overhead supplies can be flown on either wooden poles or steel pylons with either pole mounted or floor standing transformers. The underground supply cable is single phase cable running in groups of three, each cable being single stranded copper conductor with either a stranded or solid, aluminium or copper shield. Modern underground cable uses cross linked polymers for the insulation. This is very stable both with temperature and time and can withstand prolonged use at high temperatures without failure. The distribution is normally wired in a closed ring with several supply points into the ring. This allows for maintaining of the supply should a failure occur in any of the supply points or at any point on the ring.

6) The 33 kV supply voltage is further reduced to 11 kV. This voltage is supplied, among others, to light industry and hospitals. Distribution can be either overhead or underground. Overhead distribution is normally on wooden poles with pole mounted transformers supplying small rural comunities. For underground distribution single construction three phase cables are normally used with a similar distribution topology to 33 kV. A major difference between the two distribution methods is the addition of normally open points on the 11 kV ring.

7) Final distribution voltage 240V single phase / 415V three phase. Supplied to private houses, shops, offices and small businesses. In rural communities, for short distances, the supply may be via wooden poles from a pole mounted 11 kV / 415V transformer. In the past this distribution was via seperate conductors but the modern method is to use bunched cables with three phases and neutral. In urban communities an underground, three phase, single construction cable is laid geographically close to the premises needing supply and from this run of cable a 'T' joint will allow the last drop into premises for either a single or three phase supply.

1.4 Overview of Communications on LV networks

Given the size and complexity of the electricity distribution network there are many areas where communications may be possible, with each part of the network having several areas requiring research. The choice for this research was made on the following points. Of the different voltages and topologies present, the low voltage, final drop, would seem to be the area which would offer the highest return on any investment. This is because of the vast number of people connected to this part of the network. The uses for communications via the higher voltage networks could be an area for research but the uses are probably more limited to load control and network management than for general communications. It is already common practise for electricity supply companies to include fibre optic cables along with power cables on the high voltage distribution network. Compared to the bandwidth available on a fibre the signals that could be distributed alongside, via the power cable, would be so small as to be insignificant.

Previous research into mains borne communications has tended to concentrate on VLF systems of 150 kHz or below. In this range achievable data rates are low and the channel is known to be noisy [Ref. 2]. Design of filters for cutting off power frequency signals while passing communication signals and vice versa, requires physically large components because of the low frequencies involved. Above this frequency there has been very little research, mainly because it was thought that the attenuation would be far to high. The research was started with an open mind as to the methods and technologies to investigate and very quickly the HF spectrum showed as a means of allowing good signal propagation with low power and low radiation. The use of this frequency range for communication over power line has not allways been an option, but in recent years development of low cost VLSI technology and increased receiver sensitivity and reliability mean that state of the art technology can be employed on a large scale basis at low cost.

On the LV distribution network the opponents to good communications were expected to be:-

1) High attenuation due to the tree topology of the network causing low and high impedance points from joints and terminations where multiple signal paths cause the signal to split and reflect. This topology could also cause the phase response of the network to be unpredictable with severe phase distortions.

2) Unpredictability of propagation characteristics due to the variable loads. This means that all the items outlined in '1' above will change over time as equipment connected to the network is switched on or off.

3) Severe noise from switching transients and radio reception from within houses where unshielded cable provides the means for distribution within the house.

1.5 Summary

Since the 1989 Electricity Act the electricity supply industry can be summarised as follows.

1) Generators.

Main contributors are Powergen and National Power. Nuclear Electric remains in Government ownership and is made competitive by subsidies from levies imposed on fossil fuel generators. Since privatisation and the open market other smaller generators are constantly coming on line. These are from various sources such as wind power and natural gas. The cross-channel dc link means that France can contribute up to 15% of total usage if required. Electricity from generators is supplied as requested by the National Grid company according to a price agreed on the previous day.

2) Distribution to the RECs.

The National Grid Company owns and runs the main high voltage supergrid system consisting of 7000 km of high voltage transmission lines and 200 substations. This system is nationally controlled and it's primary roll is to maintain an efficient economic transmission system and facilitate competition in generation and supply. The National Grid Company is jointly owned by the 12 regional electricity companies.

3) Regional Electricity Companies (RECs)

Each REC has two primary tasks. These are distribution of electricity and supply of electricity. The distribution side of the business is responsible for the physical networks within the geographical boundaries of that REC. Access to this distribution network by other RECs is required on a nondiscriminatory basis. In order to increase competition, electricity for 1 MW and 100 kW customers can be sourced from a REC of the customer's own choosing. In 1998 this 100 kW limit will be removed and all users may purchase electricity from any supplier. Charges from the local REC will be imposed for the use of the network for distribution.

Since privatisation each REC is responsible to its shareholders for returning maximum profit on any assets. This research should enable a new market to be opened up that can compete with more traditional methods of communications on equal footing.

The majority of the communication highway is already in place waiting for a technology that can best use the available bandwidth on the network.

One of the major points in favour of this new technology is that it can be retro-fitted, quickly, without major disruption to customers or their neighbours.

This technology can provide, amongst others, telephony and associated data services, broadcast televisual information in a format similar to teletext, home security information or any combination of these and other services.

Chapter 2. History of power line communications

2.1 Introduction

As early as the 1850's, before electricity distribution was envisaged, multiple communication signals had been used down single wires, either by frequency division multiplexing or time division multiplexing (telegraph). Power lines therefore were, from early in the development of the distribution network, thought to be capable of supporting control signals along with power transmission.

From early in the development of the national grid (1930's), attempts at communications via the mains were made, in order to control the distribution and use of power generated for most economical results. Reliable communications within the electricity supply industry (ESI) is particularly important as the commodity being provided cannot be stored. If accurate information is available as to consumption and demand then substantial savings can be made by limiting the generation.

2.2 Ripple Control

Investigation into ripple control (centralised network control) for the transmission of electrical control signals started in 1929 by using frequency multiplex coding. In 1931 these methods were replaced with the introduction of impulse count coding where a number of pulses from the transmitter were injected between neutral and ground, the receiver then counted these pulses and responded to the total number with a predetermined action [Ref. 4].

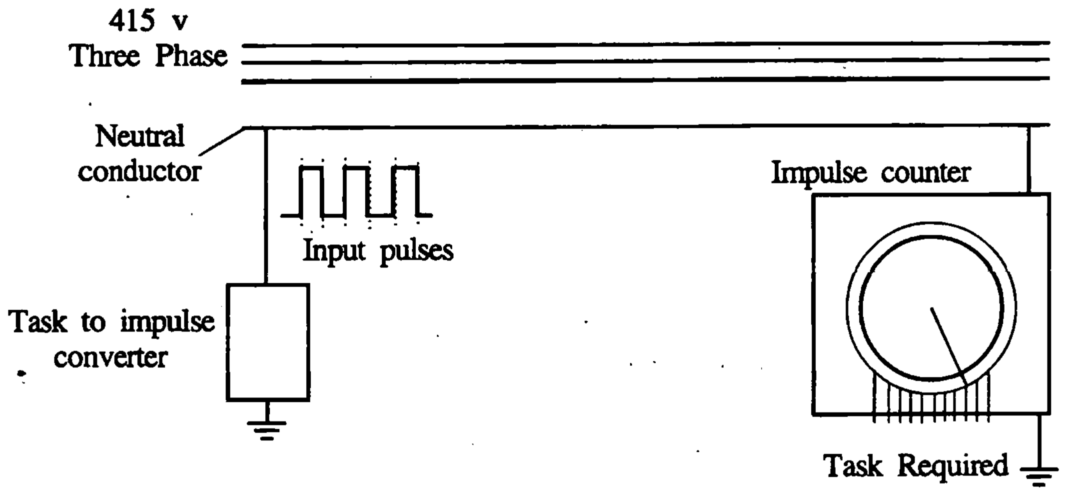

Figure 2.1. Simplified block diagram of a method of ripple control (1934)

This method of ripple control proved to be a reasonable solution but because of the complexity of the system and a limited number of unique codes it was soon superseded by impulse interval coding.

Impulse interval coding was introduced in 1936 and was adopted by virtually all Ripple Control companies. This method enabled a large number of unique events to be coded into one channel with much simpler receivers capable of service free performance for up to 30 years. The next significant improvement occurred in 1944 when the impulse format was changed from a DC pulse to a burst of audio frequency. By experiment it was ascertained that the most suitable frequencies for the impulses were between 500 and 700 Hz. In this range the harmonics of the 50 Hz power signal are still dominant so particular attention had to be paid to the design of the bandpass filters in the signal recovery part of the receiver.

From 1944 to 1968 this theory of operation remained unchanged, though significant improvement to the system was achieved by using the latest technology in both receiver and transmitter design. Present day ripple control systems are all solid state employing thyrister control to replace rotating frequency converters and they are therefore very reliable. Power for the transmitter and receivers was provided by the network.

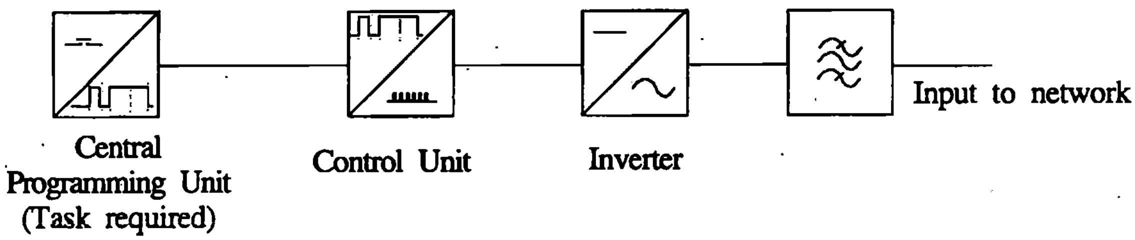

Figure 2.2. Transmitter Schematic.

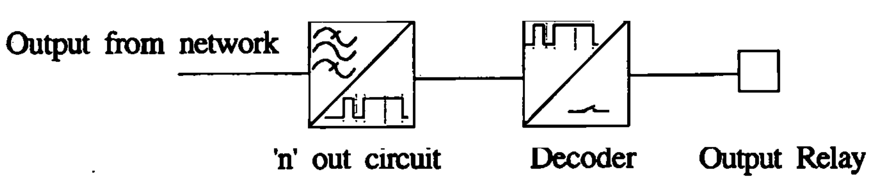

Figure 2.3. Receiver Schematic.

Signal format for ripple control.

The fundamental time period for a message on this system is 25 seconds plus start bit. This is split into 50 slots, each of which can contain a burst of audio. Before the first message pulse is the start pulse, this is longer than the signal pulses. On receiving a start signal the receiver will count the time between this and the signalling pulse or pulses. If this is the signal for which the receiver is programmed, then a response will be triggered.

Landis and Gyr formulated the following protocols for the Ripple Control system [Ref. 4].

The first 5 seconds (10 slots) are reserved for receiver address information giving 1024 unique addresses. The remaining 40 slots are divided into alternate on and off instructions for a particular task, giving switching control to 20 tasks.

Time interval 'T' = 0.5 secs

T		1		2		3		4		5	
Slot	Start bit	1	2	3	4	5	6	7	8	9	10
Address		×	×	×	×	×	×	×	×	×	×

T	6		7		8		9		10		11
Slot	11	12	13	14	15	16	17	18	19	20	21
Task	1		2		3		4		5		6
	On	Off	On	Off	On	Off	On	Off	On	Off	On

	21		22		23		24		25	
40	41	42	43	44	45	46	47	48	49	50
	16		17		18		19		20	
Off	On	Off	On	Off	On	Off	On	Off	On	Off

Figure 2.4. Landis and Gyr Ripple Control Protocols

2.3 Peak Depression.

In the late 1950s the London Electricity Board developed a system for marking the mains power signal that offered inexpensive production and maintenance costs [Ref. 5]. This method returned to the early ripple control format of marking with a single pulse rather than an audio frequency burst. The pulse was generated by applying a brief short circuit to the power signal via a thyrister causing a notch to appear on the power sine wave.

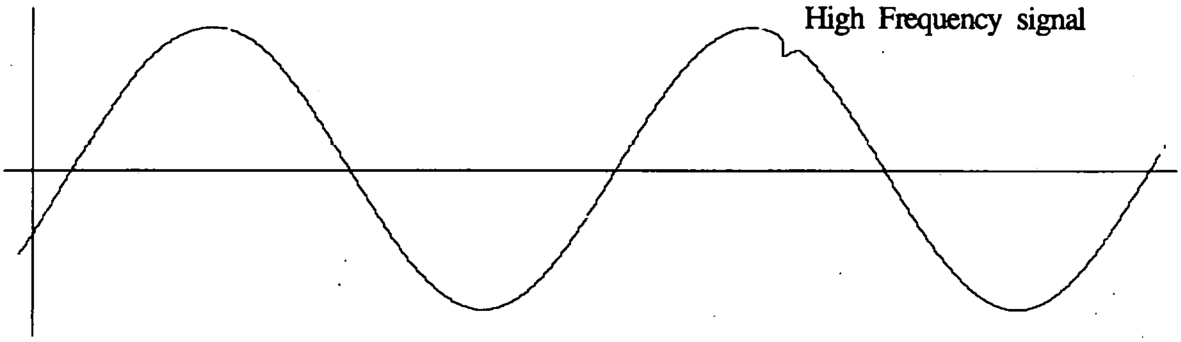

Figure 2.5. Marked and unmarked cycles of power wave

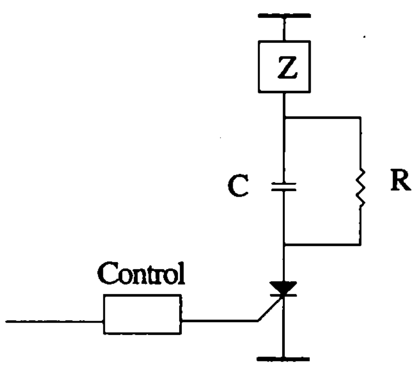

Figure 2.6. Schematic of equipment used for marking power signal.

The control device is fed from the power signal in order to maintain accurate timing between the power signal phase and the thyristor firing. When the thyristor is turned on, a current path exists between live and neutral via Z, the CR network and the thyristor. When the voltage across the capacitor C approaches the supply voltage the current will reduce to a small enough value for the thyristor to switch off. The current path through Z via R is not large enough to prevent the thyristor switching off but is large enough to discharge the capacitor before the arrival of the next potential firing point. The duration of the short circuit is controlled by the Z-C time constant. The current flow through the thyristor is between 200 and 300 amperes lasting for 30 µs.

Trials using this system were started in the Ravensbourne district of the London Electricity Board in February 1965 [Ref. 5] and continued in the Bromley area later in the same year. The protocols used for the signalling during the Bromley experiment were as follows. 'On' signals were initiated 18° before peak voltage and 'Off' signals were initiated 18° after peak voltage. A six pulse code was used with 5-cycle spacing. Spurious signals were rejected by the receiver as a result of accurate phase gating and precise message length. A full scale trial was initiated at Penge again by the London Electricity Board with 24 receivers containing event counters. Transmissions for 15 seconds every 5 minutes were made throughout each day over a period of several months. The trial was completely successful. After these trials the system was declared a success and a trial involving 88 street lamps in the Borough of Lambeth was started. For this trial a 16 cycle period was used with 3 discretely marked cycles dictating which lamp was being addressed with before peak and after peak marking dictating on or off.

2.4 Cyclocontrol

This method of mains communication has been in use continually for some time in the U.K [Ref. 6, 7]. The method of transmission is to ground the 50 Hz power signal using thyristor control several degrees before zero crossover (usually -25°) on the positive slope.

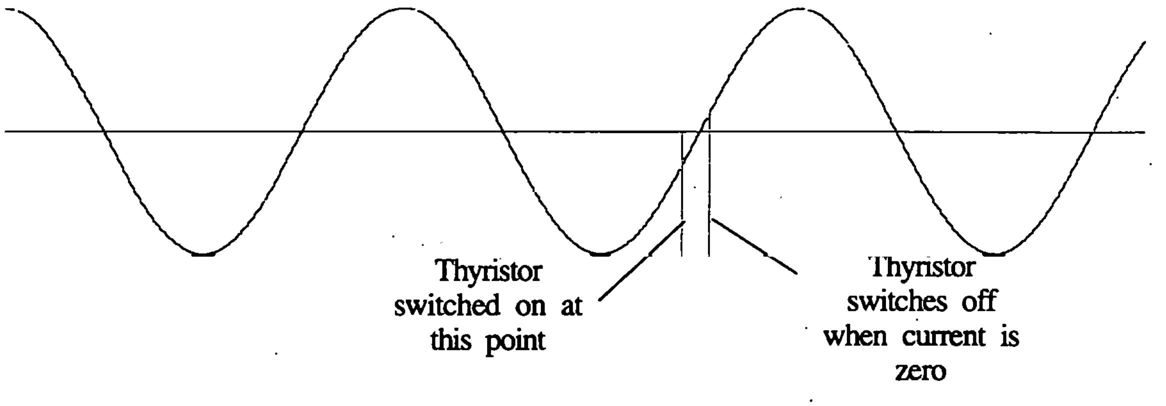

Figure 2.7. Mains supply showing thyristor on and off points.

This has the effect of "notching" the power signal. The thyristor switches off when the current passing through it is zero, this will be some time after the normal voltage zero. The phase angle of the current and therefore the delay in switch off can vary depending on load conditions on the network. For this reason the only part of the signal that can be relied upon is between the thyristor firing and the voltage zero.

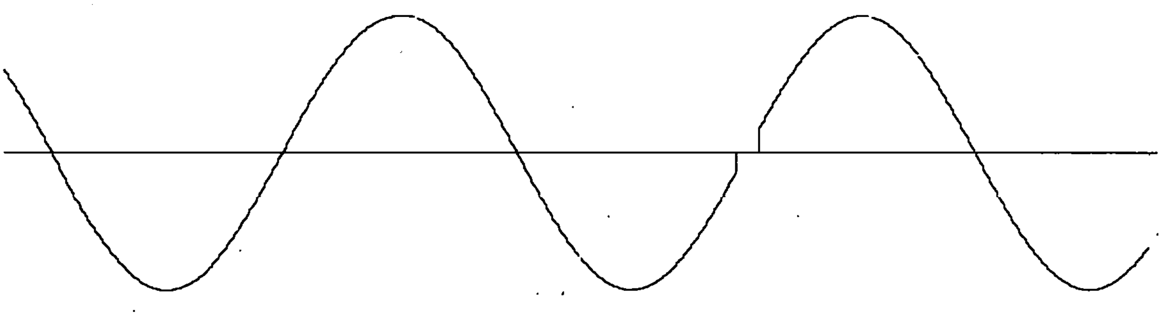

Figure 2.8. Thyristor voltage

This notch will travel throughout the network, though as the distance of transmission increases the effect of the thyristor firing will be diminished due to the line losses, mainly the cable capacitance. At the receiver it is more normal to see the waveform as shown in figure 2.9.

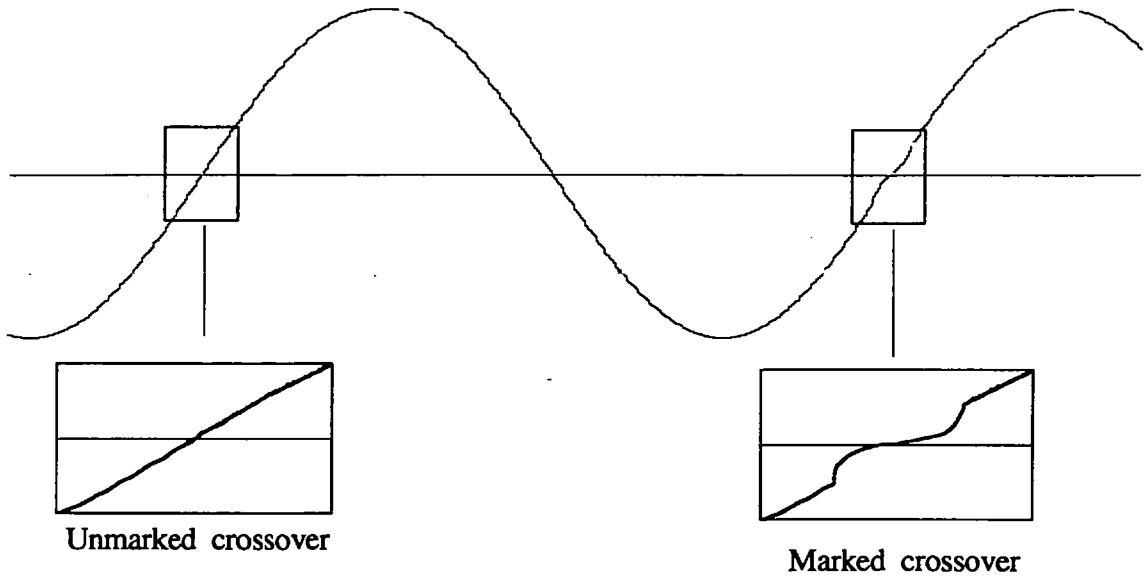

Figure 2.9. Marked and unmarked crossovers.

The amount by which the signal varies from an unmarked crossover is dependent on network loading, distance and cable types. The signal is detected by integrating the supply voltage waveform between -25° and 0°, if the result from this integration is lower on one cycle than the result for the previous cycle then the crossover is assumed to contain the signal.

That is, if $I_{(n-1)} - I_n > S_T$ where 'S_T' is a preset threshold, then the signal is present. For the purposes of signal comparison

$$S = \frac{I_{(n-1)} - I_n}{I_{(n-1)}} \times 100\%$$

'S' is normally around 10% but the signal can be correctly decoded with 'S' as low as 3%.

All the examples given on previous pages have been installed and in some cases are still being used for lighting and other load control. The theoretical and practical work carried out in the development of these systems produced a wealth of information used by companies in later years leading to the development of several methods of signalling now commercially available either in the form of complete systems for installation or as chip sets from some of the major chip manufacturers. The results from this early work were also used in the development of the standards being adhered to by these manufacturers. The following is one example of such a system.

2.5 Thorn EMI

Considerable investment by Thorn EMI has resulted in a viable system of mains communication employing spread spectrum techniques. There are several large test installations in operation and the methods and hardware of the system are complete [Ref. 8].

The system offers bidirectional communications between the LV substation and the customer termination via the LV distribution network. The communication path between the LV substation and the Data Control Centre is via standard PSTN lines.

The modulation techniques used for the Thorn system are spread spectrum and the frequencies used follow the Cenelec standard 50065 for low voltage signalling. The system provides full duplex with data rates of 200 bits per second (bps). The spread spectrum signal covers the band 40 kHz to 95 kHz and using a low impedance source tries to maintain a signal level of 1.2 volts RMS irrespective of network impedance, resulting in an average injected power of approximately 10μW/Hz/phase [Ref. 8] giving a total injected power of approximately 1.65 Watts.

The total system comprises three main parts [Ref. 8, 9] :

1) The Home Unit for the system is placed next to the meter at the customer premises. It provides impulse counting interfaces to electricity, water and gas meters for reading purposes and load control, consumption and tariff information for optional switching of non time critical loads such as water heating. A four wire half duplex serial connection to an optional customer interface allows the user to override the system and to display billing and cost information. The unit has storage available for 48 half hourly meter readings for each utility should communication be lost and the design has a telephone interface built in for normal PSTN communications if required. An on board clock is synchronised to the central controller if required.

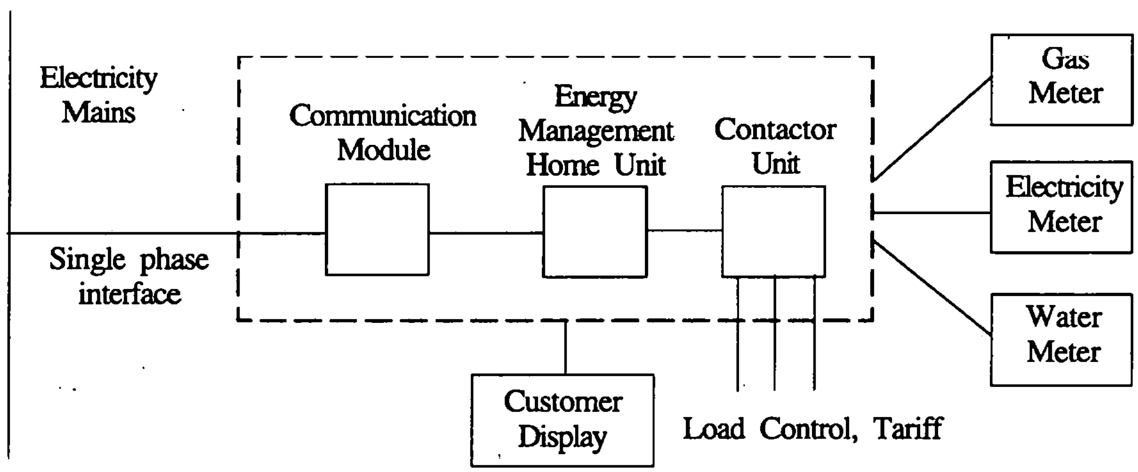

Figure 2.10. Block diagram of home unit and display

2) The Central Controller (CC) is situated in the 11 kV/415 V substation. It communicates with up to 1024 Home Units on the LV distribution network via the supply cable using either individual, group or broadcast modes. It also conveys information to and from the Data Control Centre via the PSTN telephone network or pilot wires. Temporary storage is available for holding information should either the uplink or downlink be unavailable. A battery backed real time clock calendar is installed for continuity in the event of power failure.

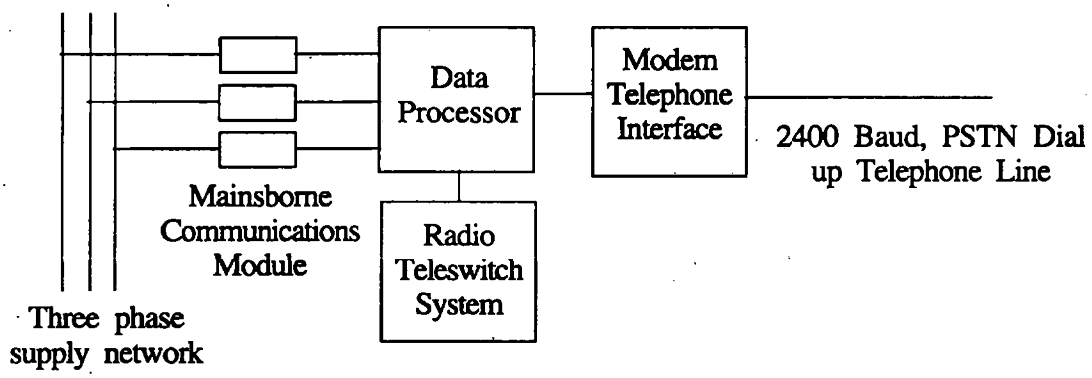

Figure 2.11. Block diagram of LV sub installation

3) The Data Control Centre can, at present, control up to 8000 units on several different LV networks. It controls all remote meter reading and load management operations provided by the system, both uploading and downloading of billing information and controls the mainsborne communication system.

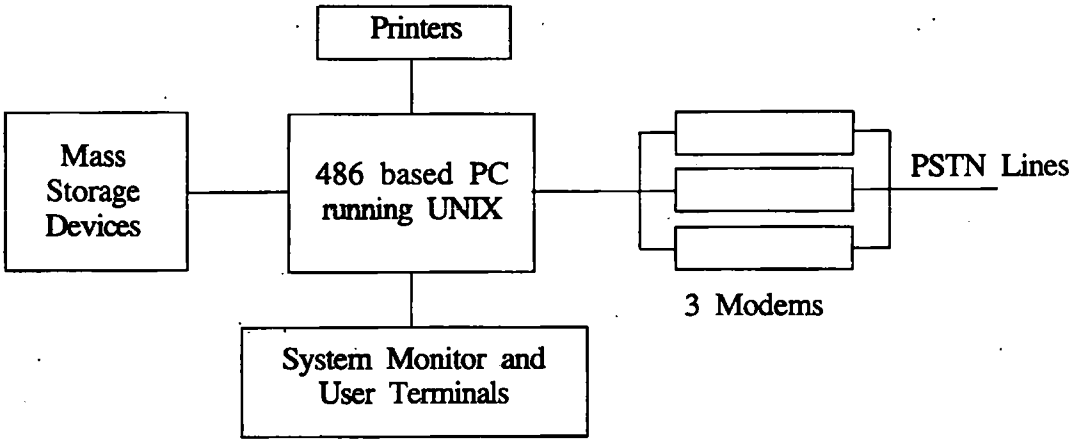

Figure 2.12. Block diagram of Data Control Centre

2.6 Summary

All of the current and past mains borne signalling systems investigated during this research use VLF methods irrespective of the modulation system used (See appendix 1). The research documented in this thesis concentrated on the HF band, for this reason comparisons between this system and others cannot easily be made. There are however two important points to note. HF systems require far less injected power for a given distance and can support far higher raw data rates than all the others. Using the HF band between 1 MHz and 10 MHz, assuming a standard modulation technique such as amplitude modulation or narrowband FM modulation, it is expected that 900 standard analogue speech channels can be installed. It is known that each of these channels can support a data rate of over 9600 baud, giving a total uncompressed raw data rate in the order of 10 Mbits.

This data rate can be increased by using superior modulation techniques and data compression techniques. At this time it is not possible to give a more accurate figure as the research is continuing and the most bandwidth efficient modulation technique is not known. Several spread spectrum techniques have been tested but these failed to sustain communication because of the unpredictable phase response of the networks involved. Some work has been done on the feasability of using an OFDM (orthogonal frequency division multiplexing) system but as yet no practical system exists though the theory seems to suggest this to be the best system so far.

Chapter 3. Transmission Lines

3.1 Introduction

This chapter will derive the equations needed to apply transmission line theory to the cables used in distribution networks. Both single and three phase equations are developed and the methods of applying these sets of equations to a network with both single phase and three phase distribution cables.

Transmission line theory is applied in order to determine impedances, voltages and currents within the network under investigation, to understand and correctly terminate the network ensuring maximum transfer of signal from source to load.

The following analysis is applicable where the electromagnetic signals are of the same order of wavelength as the length of the transmission lines used [Ref. 10]. If this is not the case then waveguide theory must be used.

This theory assumes the transmission lines to be of constant characteristics electrically, that the signal has an out and return path and that the TEM wave is the method of propagation where both the E and H waves are perpendicular to the direction of propagation at all times.

When a voltage is applied to one end of a transmission line, the waveform travels down the line with a propagation velocity that is determined by the characteristics of the line. When the wave reaches the end of the line it is either totally reflected, partially reflected or totally absorbed by the load, depending on the characteristics of the line and the termination impedances. Any reflected power will cause standing waves to appear on the transmission line giving maximum and minimum values for the voltage and current. The wavelength of this standing wave is determined by the relationship between the line characteristics and the load characteristics. In order to obtain maximum power transfer into the load, the load parameters should match the line parameters. It is necessary to know how the vector sum of the incident and reflected waves changes the signal level as the distance from the sending end varies in order to determine the voltage across the load or at any other point along the line.

With any electrical circuit the only parameters affecting signal flow are impedance and admittance. The impedance can be split to give a real, fixed, resistance and a frequency dependant inductance. The admittance can be split to give a real, fixed, conductance and an imaginary, frequency dependant capacitance. With a normal electrical circuit these components are discrete and act upon the circuit at some fixed point. With transmission lines these circuit components are continuous throughout the length of the line. However, an equivalent circuit can be described whose effect is the same as the continuous transmission line, the equivalent circuit being composed of lumped impedance and admittance values.

3.2 Single Phase Transmission Lines

In single phase transmission lines the impedance and admittance are modelled as follows.

Impedance

1) Resistance (R, ohms). The conductors of the line offer resistance to current flow. This figure includes the out and return resistance.
2) Inductance (L, henrys). An inductive reactance associated with the line because signal levels vary with time. This inductance is determined by the physical geometry and materials of the conductors.

Admittance

3) Conductance (G, siemens). Because of the nature of the insulator between conductors a small amount of current leakage occurs.
4) Capacitance (C, farads). The conductors and the insulator between the conductors form a capacitor.

The figures quoted for these parameters are usually for a one metre length of line. For the total values these must be multiplied by the length of line. The continuous nature of these parameters is catered for by representing the line as shown in figure 3.1.

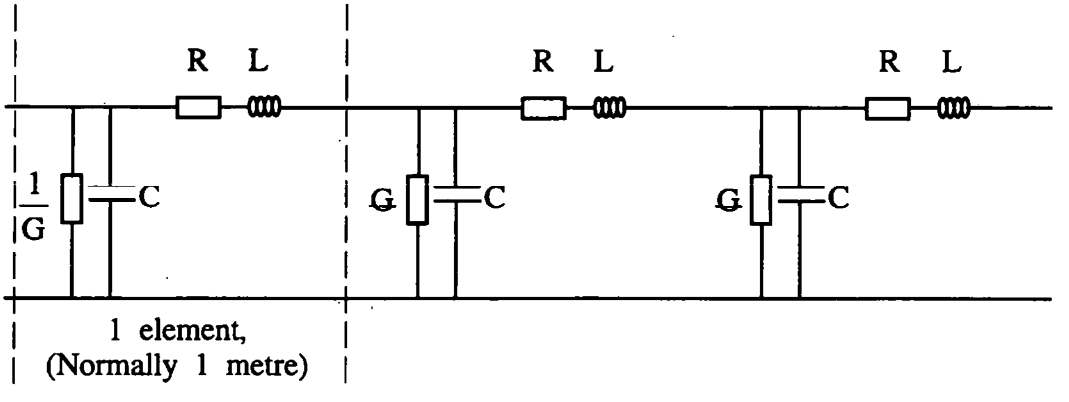

Figure 3.1 Single phase transmission line equivalent circuit

By considering one of the elements shown in figure 3.1 the voltage and current relationship to distance from the sending end can be calculated.

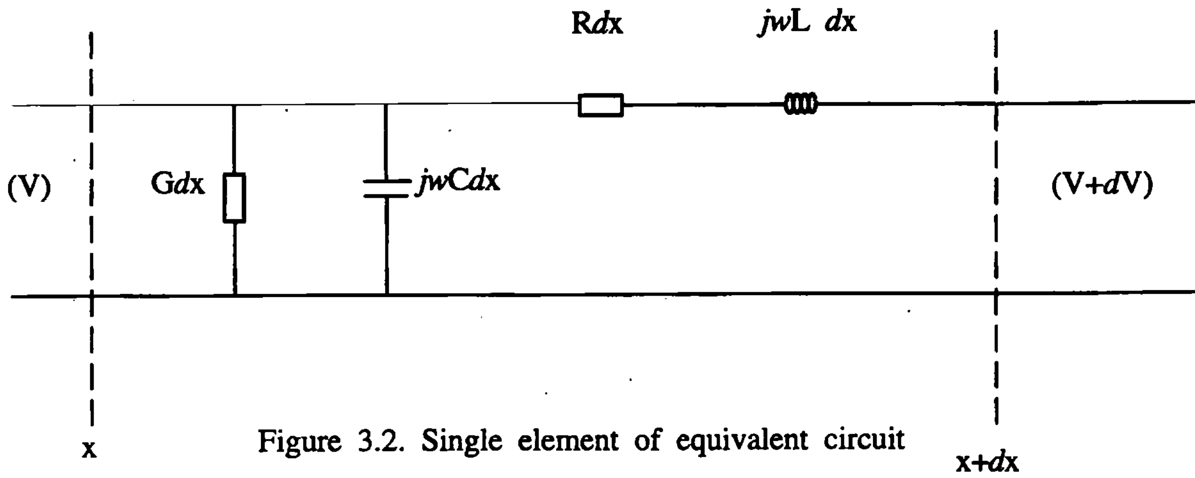

Figure 3.2. Single element of equivalent circuit

Consider figure 3.2 where R, L, G and C are the lumped values for the length *d*x.

Rate of change of voltage (V) $-dV = (R+jL)dxI$ (1)

Rate of change of current (I) $-dI = (G+jC)dxV$ (2)

Differentiating equation 1 wrt distance (x) and substituting for I from equation 2 gives :-

$$\frac{d^2v}{dx^2} = (R+j\omega L)(G+j\omega C)V \qquad (3)$$

Following standard notation, $\gamma = \sqrt{(R+j\omega L)(G+j\omega C)} = a+jb$ (4)

By substituting equation 4 into equation 3 it follows that:

$$\frac{d^2V}{dx^2} = \gamma^2 V \qquad (5)$$

where γ is the propagation constant of the line.

Similarly

$$\frac{d^2I}{dx^2} = \gamma^2 I \qquad (6)$$

Following reference 10, the general solution of equation (6) is :-

$$I = M \cosh \gamma x + N \sinh \gamma x \tag{7}$$

and from equation (5)

$$V = A \cosh \gamma x + B \sinh \gamma x \tag{8}$$

Substituting for I from equation 7, in equation 2 and using equation 8

with the standard notaion of $Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$ gives :- (9)

$$A \cosh \gamma x + B \sinh \gamma x = -Z_0 (M \sinh \gamma x + N \cosh \gamma x) \tag{10}$$

Similarly substituting for V from equation 8, in equation 1 and using equation 9 gives :-

$$A \sinh \gamma x + B \cosh \gamma x = -Z_0 (M \cosh \gamma x + N \sinh \gamma x) \tag{11}$$

(equation 10) $\times \cosh \gamma x$ - (equation 11) $\times \sinh \gamma x$ gives: $N = -\frac{A}{Z_0}$ (12)

(equation 11) $\times \cosh \gamma x$ - (equation 10) $\times \sinh \gamma x$ gives: $M = -\frac{B}{Z_0}$ (13)

This results in $I = -\frac{B}{Z_0}\cosh\gamma x - \frac{A}{Z_0}\sinh\gamma x$ (14)

If a line is terminated in Z_r,

$$\text{when } x = 0,\ V = V_s \qquad \text{and when } x = l,\ \frac{V}{I} = Z_r \tag{15}$$

Therefore from equation 8 and equation 10, $A = V_s$

and
$$B = -V_s \frac{Z_0 \cosh \gamma l + Z_r \sinh \gamma l}{Z_r \cosh \gamma l + Z_0 \sinh \gamma l} \tag{16}$$

Equation (8) becomes:
$$V = V_s \frac{Z_r \cosh \gamma(l-x) + Z_0 \sinh \gamma(l-x)}{Z_r \cosh \gamma l + Z_0 \sinh \gamma l} \tag{17}$$

equation (14) becomes:
$$I = \frac{V_s}{Z_0} \times \frac{Z_0 \cosh \gamma(l-x) + Z_r \sinh \gamma(l-x)}{Z_r \cosh \gamma l + Z_0 \sinh \gamma l} \tag{18}$$

and
$$Z = Z_0 \frac{Z_r \cosh \gamma(l-x) + Z_0 \sinh \gamma(l-x)}{Z_0 \cosh \gamma(l-x) + Z_r \sinh \gamma(l-x)} \tag{19}$$

Equations 4, 9 and 15 through 19 give the ability to calculate signal characteristics at any point on the line, if the transmission line parameters and termination impedances are known.

3.3 Multi Phase Transmission Lines

Extending the analysis to multiphase transmission lines. In this case the values for impedance and admittance can be calculated from the physical structure of the multiphase cable, recognising the multipath propagation, though because of the increased number of conductors each parameter, R, L, G, C, is replaced with multiple values as follows.

i) Capacitance (C) / Conductance (G)

In single phase cable one admittance is present between the core and the screen. In three phase cables there are admittance values between each conductor and the screen and between each conductor and the other two conductors. As shown in figure 3.3

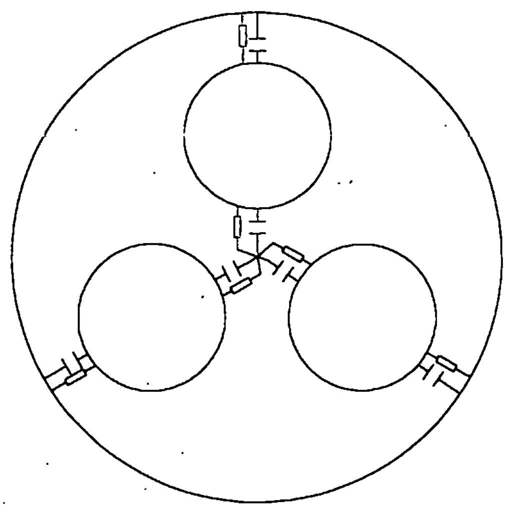

Figure 3.3. Three phase cable showing capacitance and conductance positions

ii) Resistance (R) / Inductance (L)

With single phase cable there is only one current path. In three phase cable resistance and inductance is present for each of the current paths within the cable. For the purpose of calculation these have been reduced to the three paths, out via the central conductor and return via the screen.

← Distributed impedance for first conductor →

← Distributed impedance for second conductor →

← Distributed impedance for third conductor →

← Distributed impedance for return →

Return path

Figure 3.4.

Schematic of three phase cable showing how series parameters are present

These cable parameters can be included in a model for calculating the required propagation characteristics as follows.

Equations for solving multiphase transmission line systems were derived by Riddle, et. al. [Ref. 11]. As these equations are fundamental to this thesis they are reproduced here.

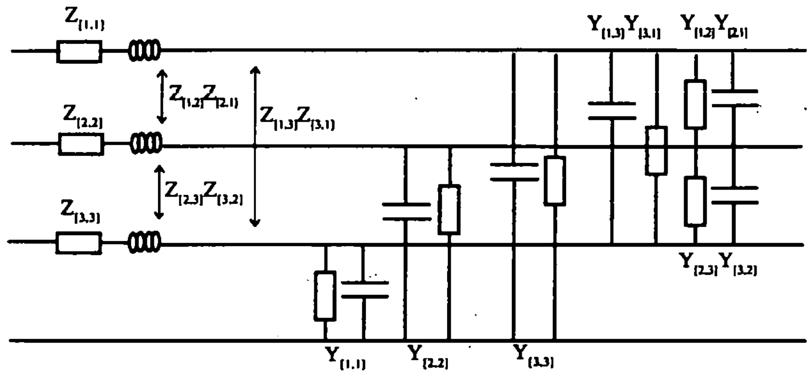

Figure 3.5. Schematic of three phase cable

Impedance per unit length matrix

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \tag{20}$$

Admittance per unit length matrix

$$Y = \begin{bmatrix} Y_{11} + Y_{12} + Y_{13} & -Y_{12} & -Y_{13} \\ -Y_{21} & Y_{22} + Y_{21} + Y_{23} & -Y_{23} \\ -Y_{31} & -Y_{32} & Y_{33} + Y_{31} + Y_{32} \end{bmatrix} \tag{21}$$

Voltage at some distance 'x' from sending end

$$V_{(x)} = \left[v_{1(x)}, \quad v_{2(x)}, \quad v_{3(x)} \right]^T \tag{22}$$

Current at some distance 'x' from sending end

$$I_{(x)} = \left[i_{1(x)}, \quad i_{2(x)}, \quad i_{3(x)} \right]^T \tag{23}$$

Propagation matrix

$$\gamma^2 = Z \times Y \tag{24}$$

Characteristic admittance

$$Y_0 = Z^{-1} \times \gamma \tag{25}$$

Reflection coefficient at the load

$$\Gamma_L = \Gamma[L] = [Z_L \times Y_0 + I]^{-1} \times [Z_L \times Y_0 - I] \tag{26}$$

The conductor voltage at distance 'x' from sending end

$$V_{(X)} = \left[I + e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right] e^{-\gamma X}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S \tag{27}$$

The conductor current at distance 'x' from sending end

$$I_{(X)} = Y_0\left[I - e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right] e^{-\gamma X}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S \tag{28}$$

The input impedance at distance 'x' from the sending end, looking towards load

$$Z_{in(X)} = \left[I + e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right]\left[I - e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right]^{-1} Y_0^{-1} \tag{29}$$

Because the only interest is in the voltage, current and impedance at ends of cables (X=L or X=0) equations 27, 28 and 29 can be simplified to give the following:

The receiving end voltage

$$V_{(L)} = \left[I + \Gamma_L\right] e^{-\gamma L}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S \tag{30}$$

The receiving end current

$$I_{(L)} = Y_0\left[I - \Gamma_L\right] e^{-\gamma L}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S \tag{31}$$

The sending end impedance looking towards load

$$Z_{in(0)} = \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Y_0^{-1} \tag{32}$$

For symmetrical three phase cables the following is true:

$$Z_{11}=Z_{22}=Z_{33} \text{ and } Z_{12}=Z_{13}=Z_{21}=Z_{23}=Z_{31}=Z_{32}, \tag{33}$$

$$Y_{11}=Y_{22}=Y_{33} \text{ and } Y_{12}=Y_{13}=Y_{21}=Y_{23}=Y_{31}=Y_{32}. \tag{34}$$

Therefore these matrix equations can be simplified as follows:

$$\text{Given that} \quad A=\begin{bmatrix} x & y & y \\ y & x & y \\ y & y & x \end{bmatrix} \text{ and that} \tag{35}$$

$$B=\begin{bmatrix} v & w & w \\ w & v & w \\ w & w & v \end{bmatrix} \tag{36}$$

$$[A\times B]_{ii}=xv+2yw \text{ and } [A\times B]_{ij}=xw+yw+yv,\ (i\neq j) \tag{37}$$

Similarly from equation 34

$$\left[A^{-1}\right]_{ii}=\frac{x^2-y^2}{x^3+2y^3-3xy^2} \text{ and } \left[A^{-1}\right]_{ij}=\frac{xy-y^2}{x^3+2y^3-3xy^2},\ i\neq j \tag{38}$$

$$\text{and given that} \quad A^2=\begin{bmatrix} x & y & y \\ y & x & y \\ y & y & x \end{bmatrix} \tag{39}$$

Equation 39 can be solved to give:

$$[A]_{ij}=\frac{\left[\pm\sqrt{x+2y}\pm\sqrt{x-y}\right]}{3},\ i\neq j \text{ and } [A]_{ii}=\frac{y-[A]_{ij}^{\,2}}{2[A]_{ij}} \tag{40}$$

Using the statements in equations 33 and 34 and applying equation 37 to equation 24 gives:-

$$[\gamma^2]_{ii} = Z_{11}[Y_{11} + 2Y_{12}] + 2Z_{12}[-Y_{12}] \tag{41}$$

$$[\gamma^2]_{ij} = Z_{11}[-Y_{12}] + Z_{12}[-Y_{12}] + Z_{12}[Y_{11} + 2Y_{12}],\ i \neq j$$

inverting the Z matrix gives:-

$$[Z^{-1}]_{ii} = \frac{Z_{11}{}^2 - Z_{12}{}^2}{Z_{11}{}^3 + 2Z_{12}{}^3 - 3Z_{11}Z_{12}{}^2} \text{ and } [Z^{-1}]_{ij} = \frac{Z_{11}Z_{12} - Z_{12}{}^2}{Z_{11}{}^3 + 2Z_{12}{}^3 - 3Z_{11}Z_{12}{}^2},\ i \neq j \tag{42}$$

and equation 25 becomes

$$[Y_0]_{ii} = [Z^{-1}]_{11}\gamma_{11} + 2[Z^{-1}]_{12}\gamma_{12} \text{ and}$$

$$[Y_0]_{ij} = [Z^{-1}]_{11}\gamma_{12} + [Z^{-1}]_{12}\gamma_{12} + [Z^{-1}]_{12}\gamma_{11},\ i \neq j \tag{43}$$

Before these equations can be incorporated into a computer programme to provide the voltages and currents for multiphase transmission lines the transmission line parameters must be obtained.

3.4 Calculation of Transmission line Parameters.

3.4.1 Introduction

The calculation of transmission line parameters for single phase cables is straightforward because of the symmetry of these cables. For the three phase cables the calculation of parameters is difficult because of the non-symmetrical and variable construction methods used in manufacture of the cables. The following shows one method of approaching the problem.

3.4.2 Circular Conductor Cables

<u>Screen/Core Capacitance and Conductance of cables</u>

The calculation of capacitance and conductance for single phase transmission lines is achieved, using the equations for concentric cylinders (length = 1 metre):

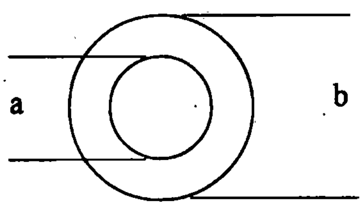

Figure 3.6: Concentric Cylinders

$$C = \frac{2 \times \pi \times \varepsilon}{\ln \frac{b}{a}} \tag{44}$$

For multiphase transmission lines the central conductors are not concentric with the screen and these equations are not valid.

Establishing the relationship between a single, non concentric, circular conductor and capacitance/conductance/inductance can be done using a variety of methods. The theoretical method involves conformal transformations [Ref. 12] and yields the equation:

$$C = \frac{\pi\varepsilon}{A\cosh\left[\frac{a^2+b^2-d^2}{2\times a\times b}\right]} \text{ and } G = \frac{\pi\rho}{A\cosh\left[\frac{a^2+b^2-d^2}{2\times a\times b}\right]} \quad (45)$$

Two other methods are available. These are, finite element analysis and experimentation. Both of these methods involve a series of tests with various core sizes and displacements and the extraction of an empirical equation to fit the results. In order to assess the validity of the finite elements and experimental methods these were performed and the results compared to the above equation.

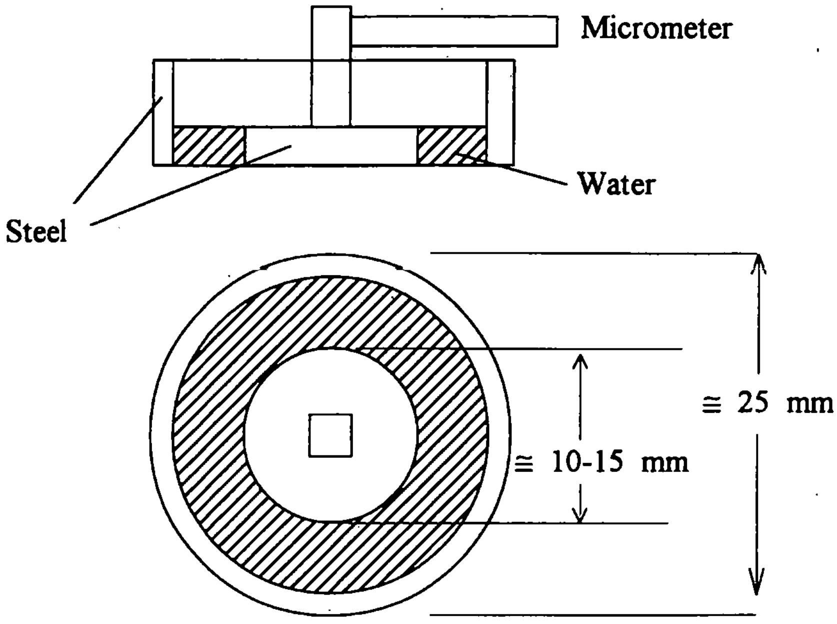

Figure 3.7. Test equipment used for measuring conductance

With the micrometer it was possible to position the central conductor accurately within the outer conducting ring.

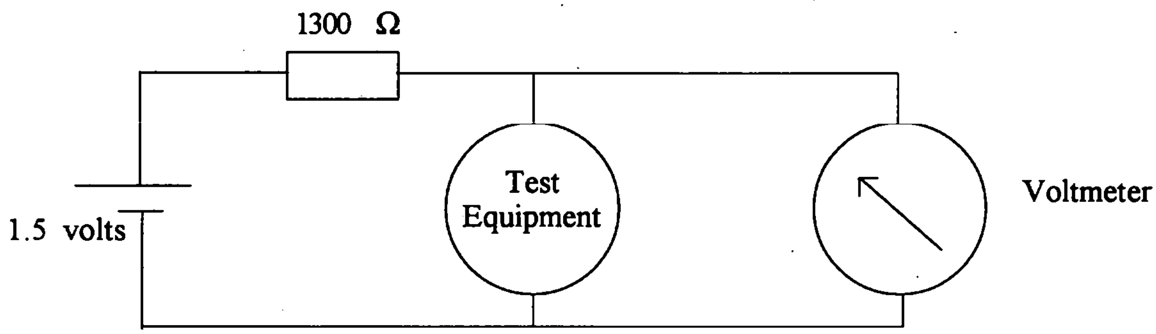

Figure 3.8. Circuit Diagram of Test Setup

Using the equipment shown in figures ~~3.5~~ 3.7 and ~~3.6~~ 3.8, a profile of voltage versus distance was obtained. In this application capacitance and conductance are related to each other such that any equation developed for calculating capacitance can be used to calculate conductance by replacing permittivity with conductivity.

Because of this similarity, the experiments would be carried out on the conductance, it being easier to measure and not subject to fringe effects.

With a hole diameter 'b' of 22.4 mm, a core diameter 'a' of 15.4 mm and a thickness 'l' of 3.6 mm, the following table was recorded.

Displacement mm	Voltage volts	Measured Conductance siemens
0	0.927	0.000475
0.5	0.923	0.000481
1	0.911	0.000497
1.5	0.878	0.000545
2	0.838	0.000608
2.5	0.778	0.000714
3	0.68	0.000928
3.5	0.548	0.001336

Table 3.1. Voltage and Conductance versus Displacement from centre.

With '0' displacement the conductance from equation 44 gives $\sigma = 7.726\times10^{-3}$

As displacement varies the conductance/displacement relationship can be described by:-

$$G=\frac{2\times\pi\times\sigma\times l}{\ln\frac{b}{a}}[1+f(d/b,a/b)] \qquad (46)$$

Where f(d/b,a/b) is some function of the displacement 'd' and the core/screen ratio. This function is 0 when the conductor is concentric with the screen. Subtracting G_0 then dividing by G_0 gives the graph in figure 3.9.

This graph represents the unknown function X=[f(d/b,a/b)]

In this particular case the core diameter is fixed. This reduces the function to X=[f(d/b)].

Using the data from table 3.1 it is possible to map certain functions to fit the graph. Using the method of least squares (regression) the following functions were tried giving the graph shown in figure 3.10 and the results shown in table 3.2.

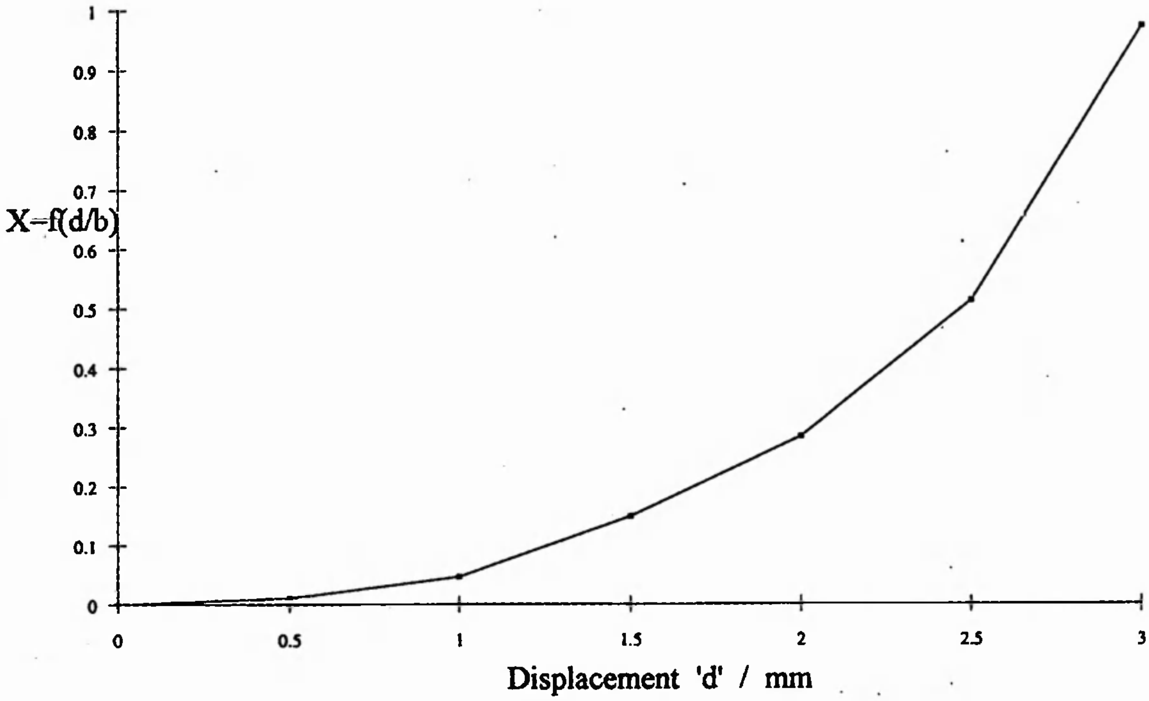

Figure 3.9. Unknown function versus displacement.

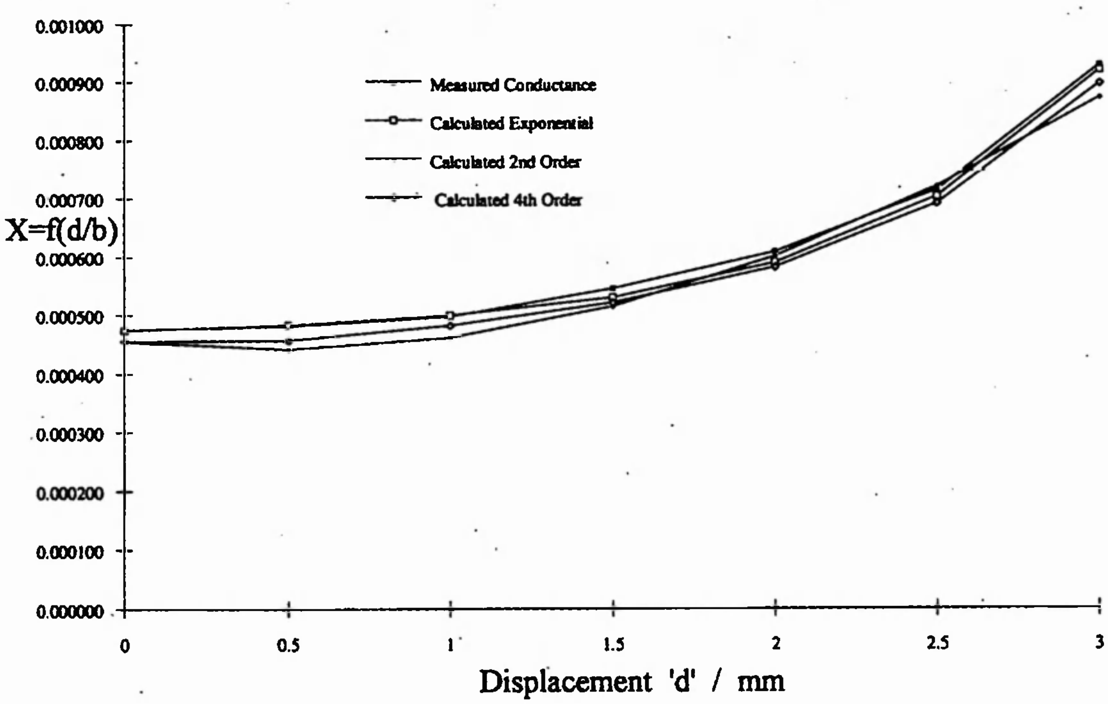

Figure 3.10.

Experimental and Calculated Results versus Displacement from centre.

	Conductance siemens			
Displacement mm	Experimental	Exponential	2nd order polynomial	4th order polynomial
0	0	0.009689396	0.000455	0.000456
0.5	0.005815856	0.016033976	0.000442	0.000456
1	0.011656699	0.026532965	0.000461	0.000482
1.5	0.035273196	0.043906654	0.000514	0.000521
2	0.071475652	0.07265657	0.0006	0.000581
2.5	0.13398008	0.120231826	0.00072	0.000691
3	0.209421053	0.198959186	0.000872	0.000896

Table 3.2. Experimental and Calculated Results versus Displacement from centre.

The equations used to calculate table 3.2 are given below in their general form.

1) 2nd order polynomial $y = ax^2 + bx + c$

2) 4th order polynomial $y = ax^4 + bx^3 + cx^2 + dx + e$

3) Exponential $y = ae^{bx}$

Of the three examples, the 4th order polynomial is the best fit. However as each of the variables 'a' through 'e' is in itself a variable in terms of the core/ screen ratio, the resulting final equation will be too complex. The 2nd order polynomial is acceptable for this core/screen ratio but on further investigation with different core/screen ratios calculated results differ significantly from the experimental results. This leaves the exponential function as the most suitable for the final implementation.

With the function of the form $X = ve^{\frac{wd}{b}}$ (47)

the coefficients $v = 19.85\times10^{-3}$ and $w/b = 1.298$ were found using least squares regression methods.

This gives a completed equation of.

$$G = \frac{2 \times \pi \times \sigma \times 1}{\ln \frac{b}{a}} \left[1 + 19.85 \times 10^{-3} \times e^{29.11\frac{d}{b}} \right], \tag{48}$$

Applying this equation gives the following:

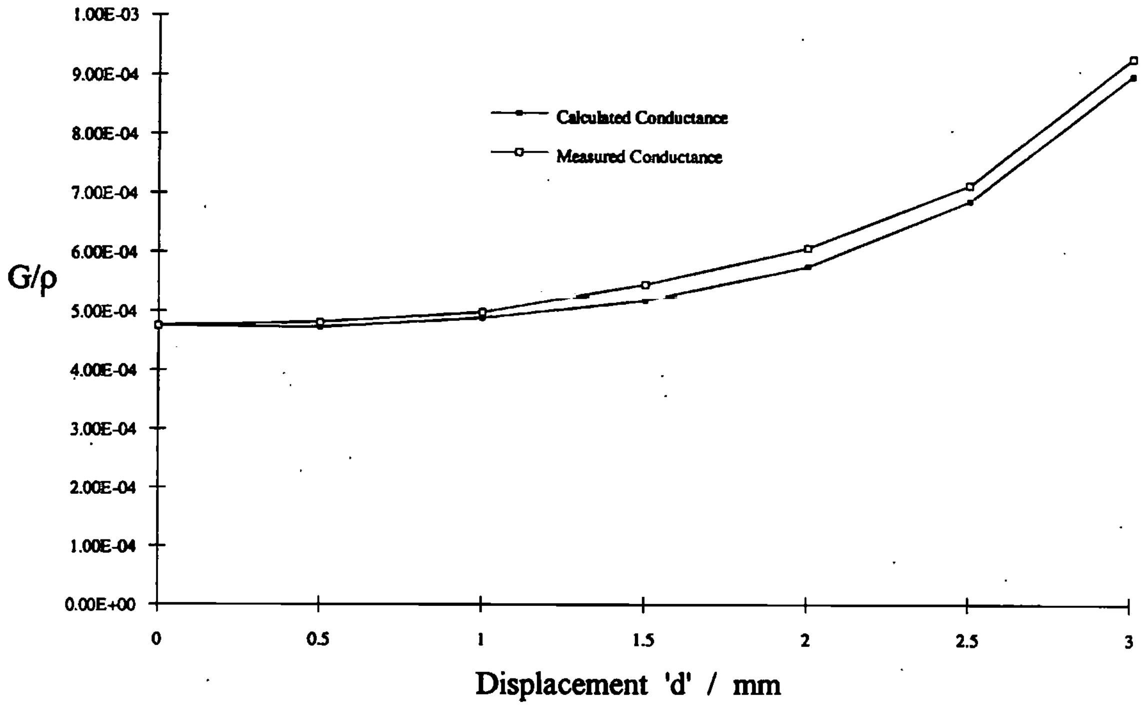

Figure 3.11. Measured and calculated conductance using equation 48.

Equation 48 gives a good approximation for the conductance of the equipment as ‘d’ varies but is only valid for the core/shield ratio used. In order to provide a general equation the experiment was repeated several times with varying core sizes producing a table of coefficients

Core Ratio	'V'	'W'
0.267618198	0.005121081	0.733773067
0.343443354	0.001147966	1.066912564
0.356824264	0.005851261	0.811224729
0.374665477	0.002061783	1.024392152
0.43264942	0.008599295	0.843237872
0.468331847	0.011378416	0.855966066
0.619982159	0.011715477	1.196282052
0.686886708	0.019858108	1.298255776

Table 3.3. 'V' and 'W' coefficients for various core/screen ratios.

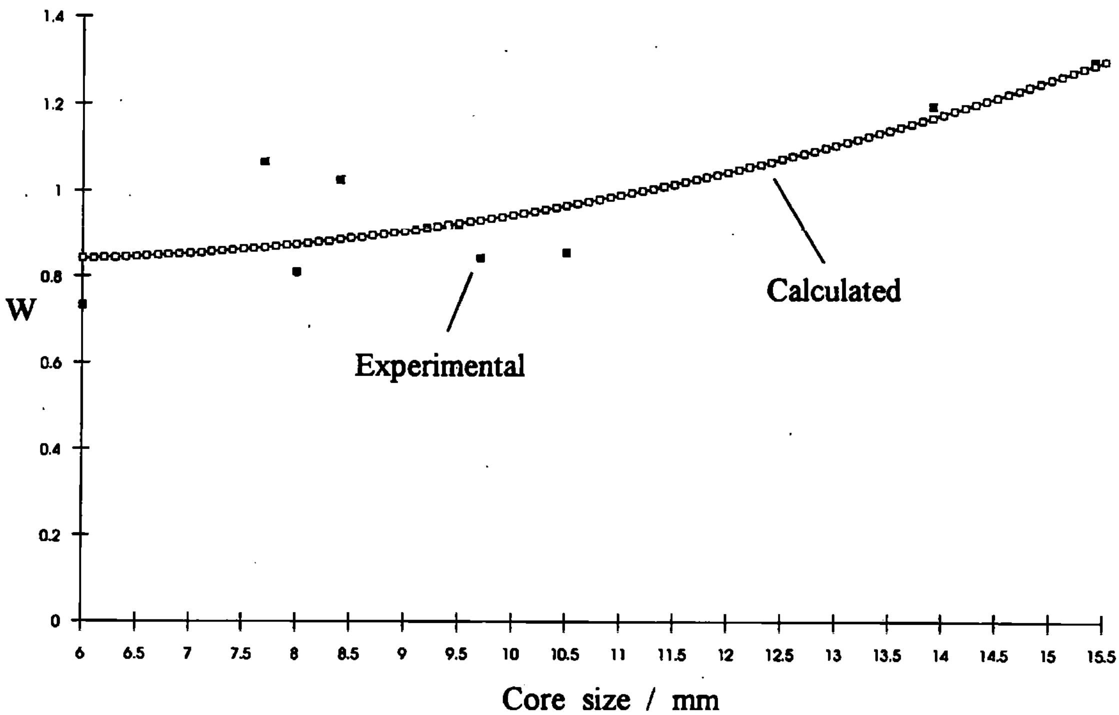

Figure 3.12. 'W' coefficient versus core size.

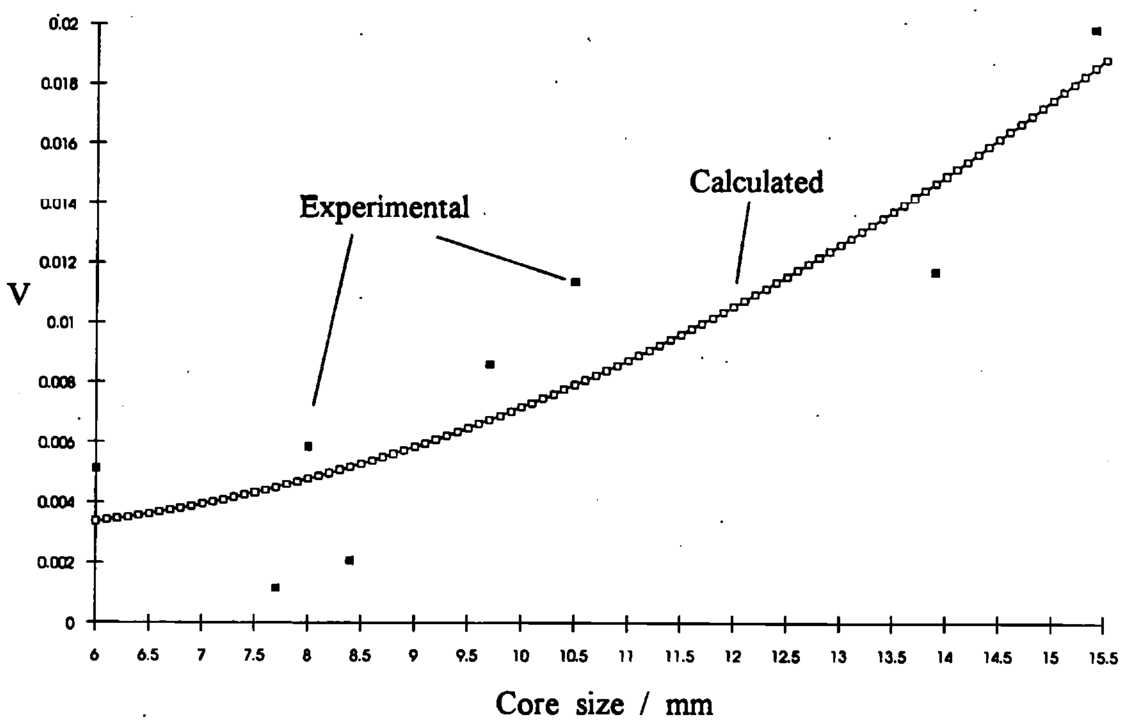

Figure 3.13. 'V' coefficient versus core size.

Figure 3.11 and figure 3.10 represent two unknown functions for calculating the coefficients of 'W' and 'V' for various core/screen ratios. In order to keep these functions simple, the function chosen was a quadratic of the form '$l \times cs^2 + m \times cs + n$' where cs is the core/shield ratio. This is a simplified form of the graph but it provides reasonable accuracy, provided the core shield ratio is within the range 0.20 to 0.7. With cables of more than two phases this ratio cannot be over 0.4 and is not normally less than 0.2.

Using the same regression methods the coefficients for 'W' are as follows.

l = 2.083341695

m = -0.9176517145

n = 0.9380957261

and the coefficients for 'V' are:

l = 0.06210013659

m = -0.2298915142

n = 0.005067872408

This gives a final equation for calculating the conductance of 1 metre of non concentric conductor as:

$$G = \frac{2 \times \pi \times \sigma}{\ln \frac{b}{a}} \left[1 + \left[0.062 \times \left[\frac{a}{b} \right]^2 - 0.0229 \frac{a}{b} + 0.0051 \right] \times e^{22.42 \times (2.083 \times \left[\frac{a}{b} \right]^2 - 0.917 \frac{a}{b} + 0.938) \frac{d}{b}} \right] \tag{49}$$

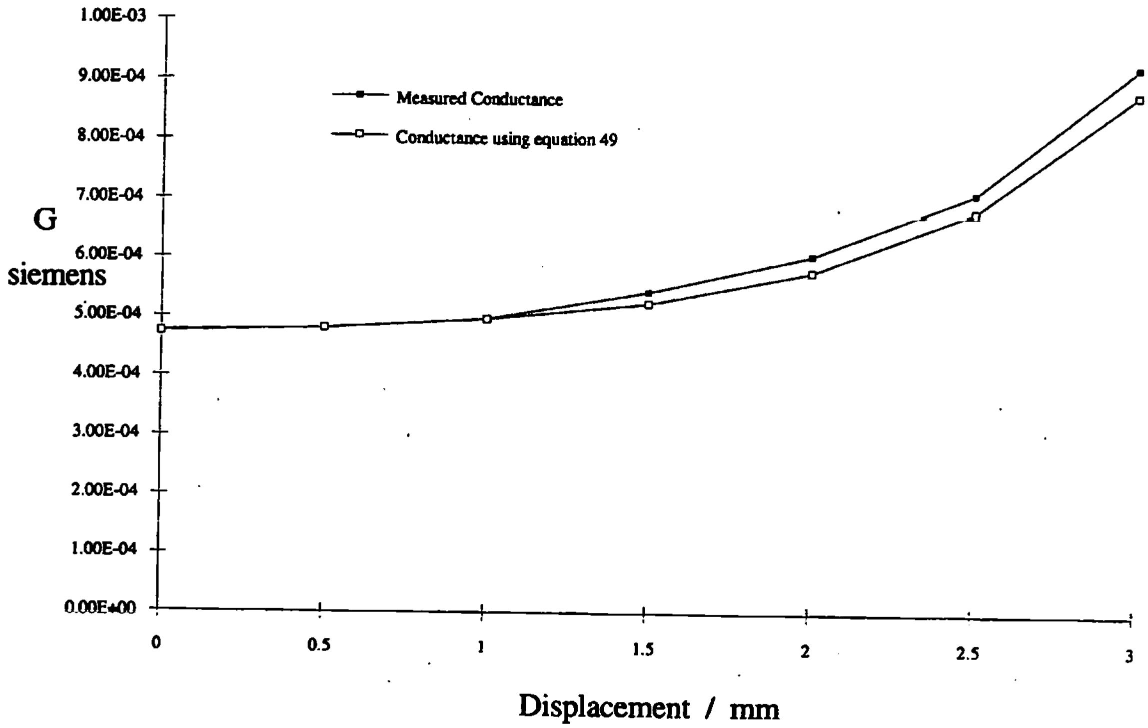

Figure 3.14. Measured and calculated conductance using equation 49.

Equation 46 can also be used for capacitance by replacing σ with ε as shown in equation 50.

$$C = \frac{2 \times \pi \times \varepsilon}{\ln \frac{b}{a}} \left[1 + \left[0.062 \times \left[\frac{a}{b} \right]^2 - 0.0229 \frac{a}{b} + 0.0051 \right] \times e^{22.42 \times (2.083 \times \left[\frac{a}{b} \right]^2 - 0.917 \frac{a}{b} + 0.938) \frac{d}{b}} \right] \tag{50}$$

The equations derived here for conductance and capacitance refer to the situation where there is one non-concentric circular conductor within a circular shield. The accuracy of the derived equation can be checked using equation 50 and the accuracy of the data can be checked using the finite element technique.

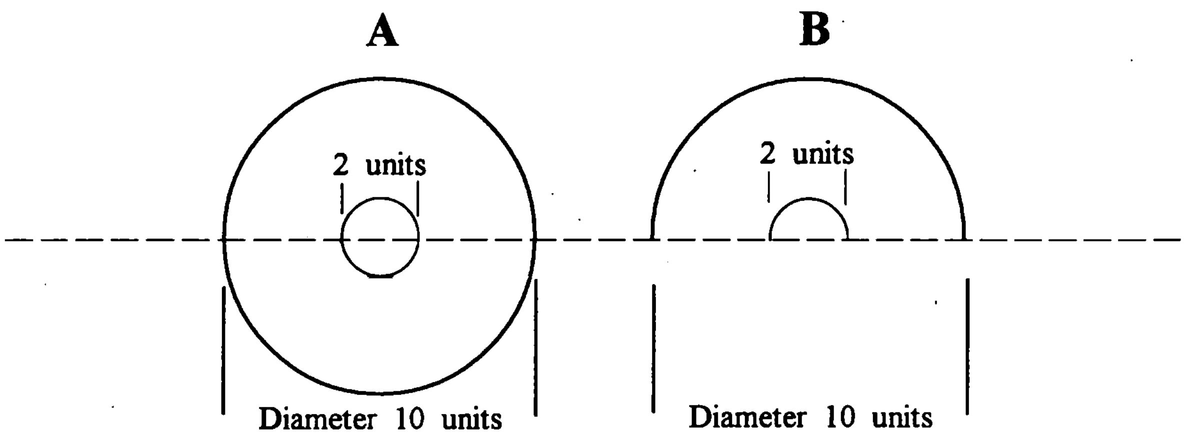

Figure 3.15.

Model Used to 'A' test equation 49 and 'B' apply finite elements

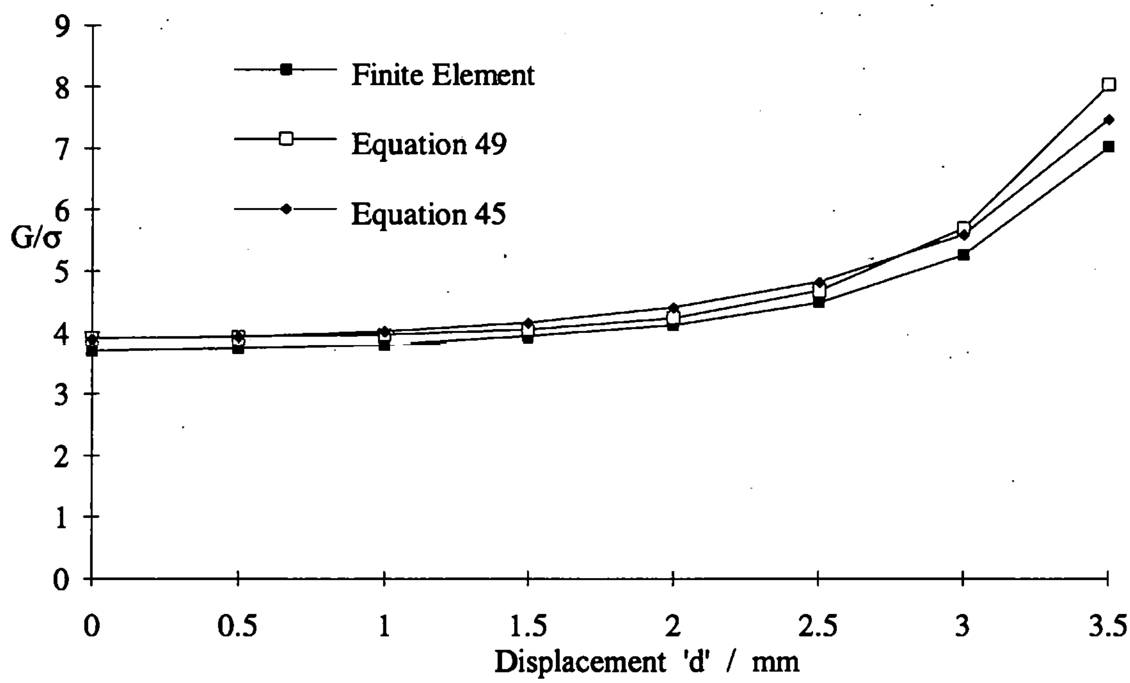

Figure 3.16.

Finite element and calculated conductance using equations 45 and 49.

From figure 3.16 all results on the single conductor cable, from the finite element model, the empirical equation and the conformal transform equation are within an allowable experimental percentage. This proves that the experimental method or the finite element method could be used to develop an empirical model of a three phase cable where a conformal transform is not possible.

3.5 Core to Core Capacitance

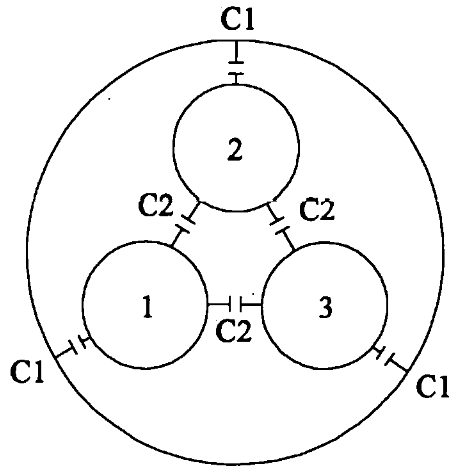

Figure 3.17. Schematic of three phase cable showing the unknown capacitances.

Because of the symmetry of the cables there are only two values of capacitance. If the three internal conductors were in free space the capacitance between any two (C2) is given by:

$$C2 = \frac{\pi\varepsilon}{\ln\left[\frac{d-r}{r}\right]} \tag{51}$$

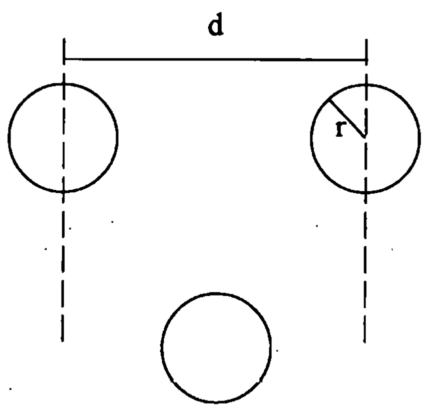

Figure 3.18. Three equidistant conductors in free space.

The screen surrounding the conductors has the effect of reducing this capacitance. The relationship between d, r and the radius of the screen can be found as before with experimentation or finite element analysis. The more accurate method is finite elements.

In order to simplify the analysis one of the three conductors was removed and the resulting schematic was split along the line XY.

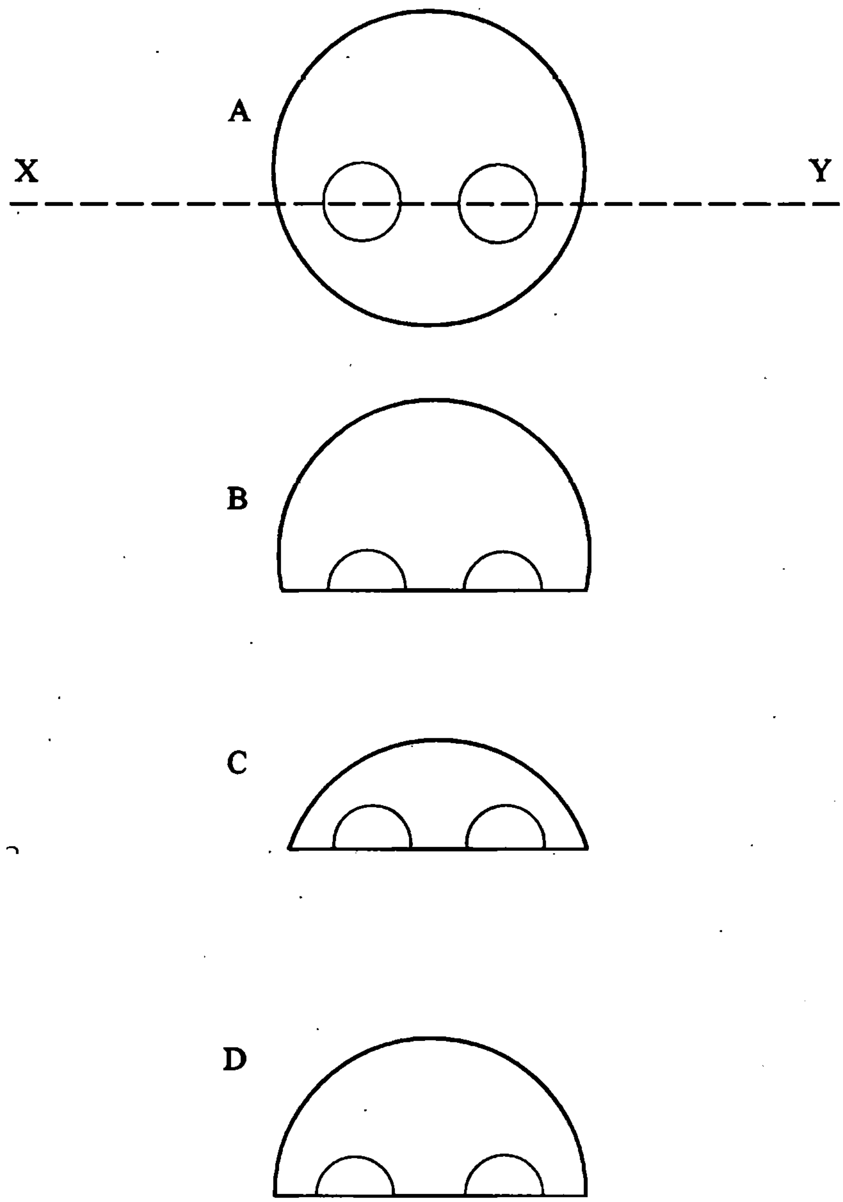

Figure 3.19. Diagram showing initial finite element implementation.

Figure 3.19 parts B and C were analysed using finite element analysis and the result compared to figure 3.19D where the two internal conductors lie on a diameter of the outer screen. The results showed little difference between the two.

With R = 5, r = 1 and d/2 = 2.68

Finite element capacitance from figure 3.19. B = 0.7615ε

Finite element capacitance from figure 3.19. C = 0.6004ε

Finite element capacitance from figure 3.19. D = 0.7124ε

Adding 'B' and 'C' gives 1:3620, multiplying 'D' by two gives 1.4248. This gives approximately 4% error in the result.

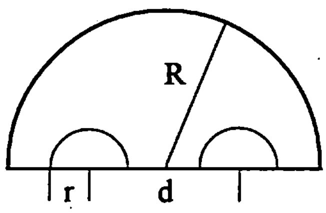

Figure 3.20. Diagram showing final finite element implementation.

Figure 3.20 shows half of the completed model, capacitance for this model needs multiplying by two to give total capacitance. Because of the symmetry of this, using the theory of ground planes this can be further simplified to the diagram in figure 3.21. [Ref. 14]

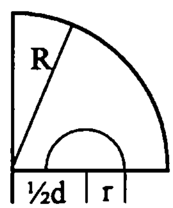

Figure 3.21. Diagram showing model used for finite element implementation.

Figure 3.21 will return twice the value for capacitance as figure 3.20 making it the correct value for two conductors on the diameter of a circular screen. It is noted at this point that absolute values for r, R and d are not needed, the capacitance only depends on the relative ratios of these values.

On modern three phase circular conductor, PVC or XPLE insulated cable, the conductor centre is 0.536 of the screen radius, from the centre of the screen. This is because the core insulation is the only insulation between cores and between core and screen giving the situation where the inside of the screen is built up of three maximum sized circular elements. This forces the conductor centre to be at 0.536 of the screen radius. Using finite element analysis on different core sizes with centres at 0.536 $\times$ R gives the table 3.4 below and figure 3.22.

r/R	Finite element capacitance
0.15	1.2225
0.175	1.3193
0.2	1.4179
0.225	1.5284
0.25	1.6543
0.275	1.7901
0.3	1.9317
0.325	2.1124
0.35	2.323
0.375	2.5665
0.4	2.8786
0.425	3.2533

Table 3.4. Experimental results of various core/screen ratios, centre at 0.536R

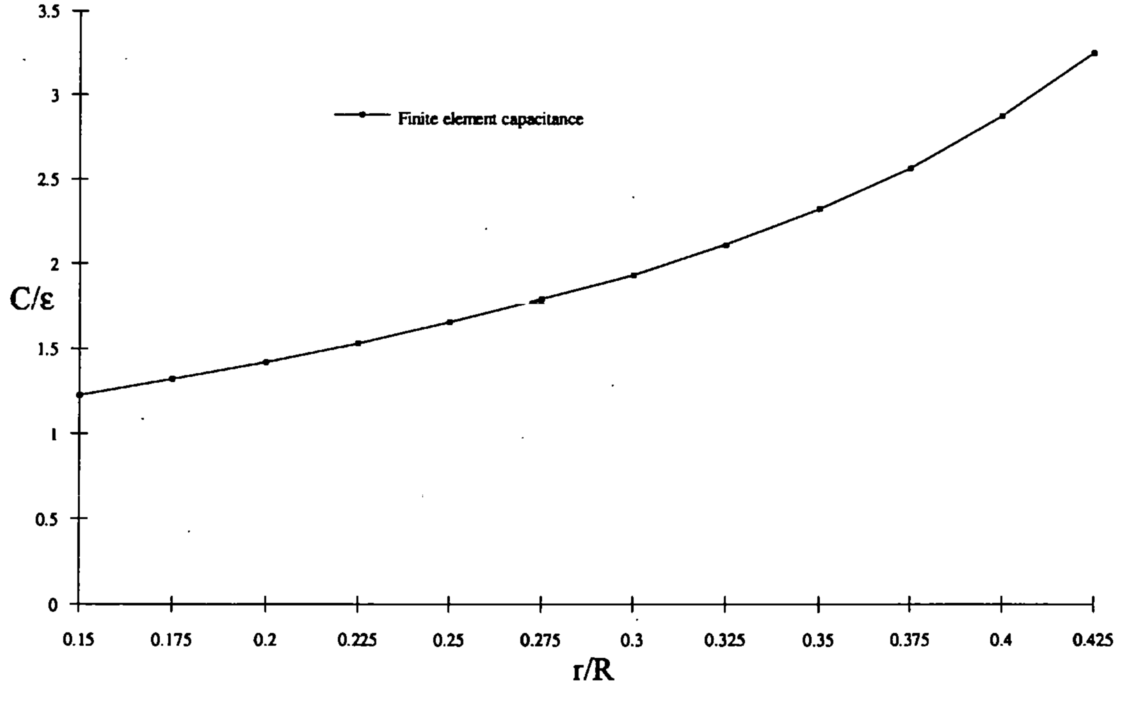

Figure 3.22. Finite Element Capacitance of Various Core/Screen Ratios.

The only types of curve for which regression methods will converge when applied to the results given in table 3.4 and figure 3.22, are the second or fourth order polynomials:

$$\frac{C}{\varepsilon} = 20.03 \times \left[\frac{r}{R}\right]^2 - 4.54 \times \frac{r}{R} + 1.50 \text{ and} \tag{52}$$

$$\frac{C}{\varepsilon} = 206.6 \times \left[\frac{r}{R}\right]^4 - 165.8 \times \left[\frac{r}{R}\right]^3 + 56.73 \times \left[\frac{r}{R}\right]^2 - 5.11 \times \frac{r}{R} + 1.17 \tag{53}$$

The results of both these equations are given in figure 3.23.

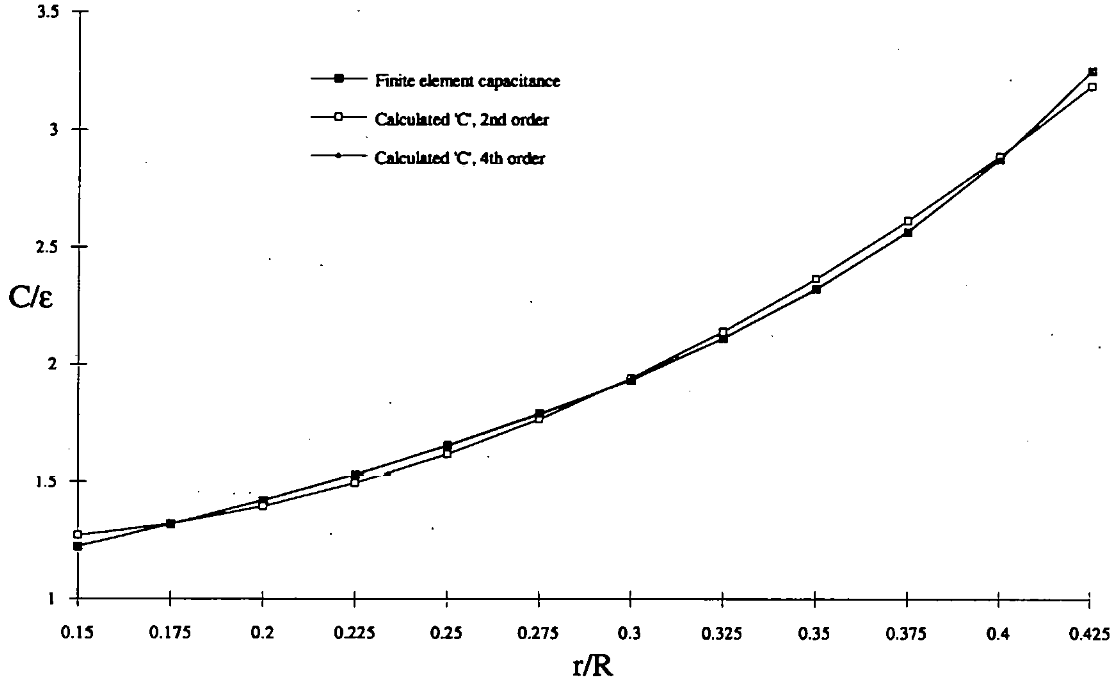

Figure 3.23. Results of various equations compared to experimental data.

Both polynomials give an acceptable fit though the 4th order is significantly better. The choice of equation depends on the accuracy needed.

On certain of the older cable and cable with pitch or paper insulation the conductor centre is not necessarily as stated earlier. For these cables the following method and equations must be used.

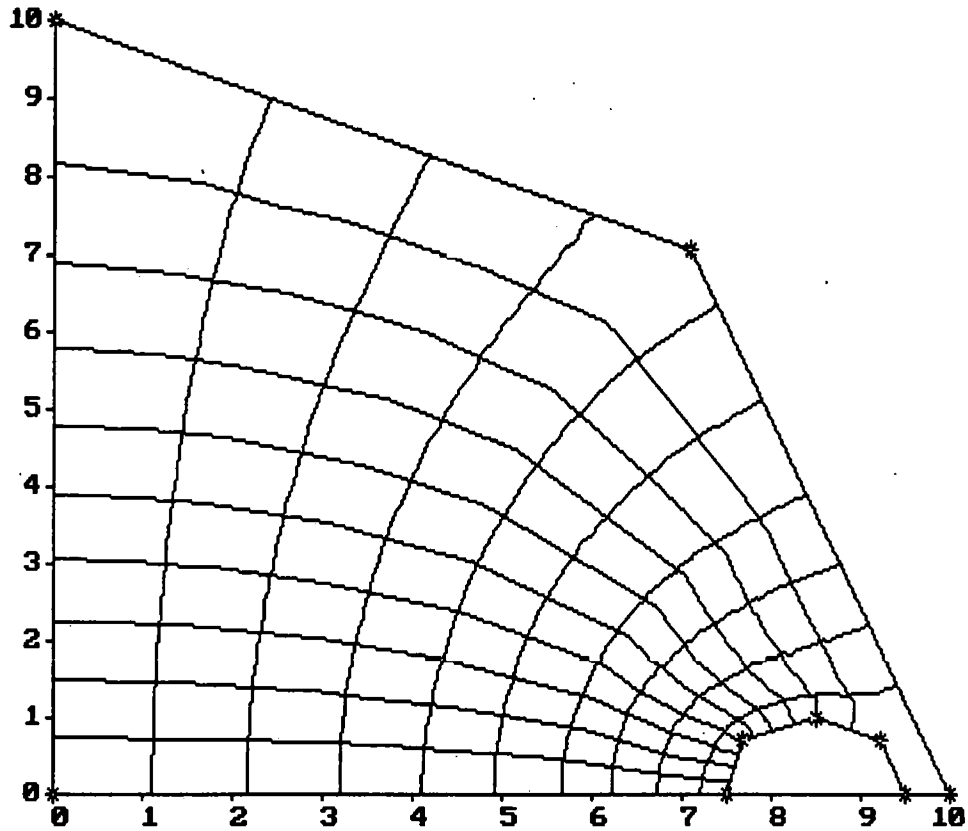

Figure 3.24. Specimen of finite element model showing r = 1, R = 10 and d = 17.

Varying 'd' on the above model produced the results shown in figure 3.25 displayed with the capacitance calculated using equation 55.

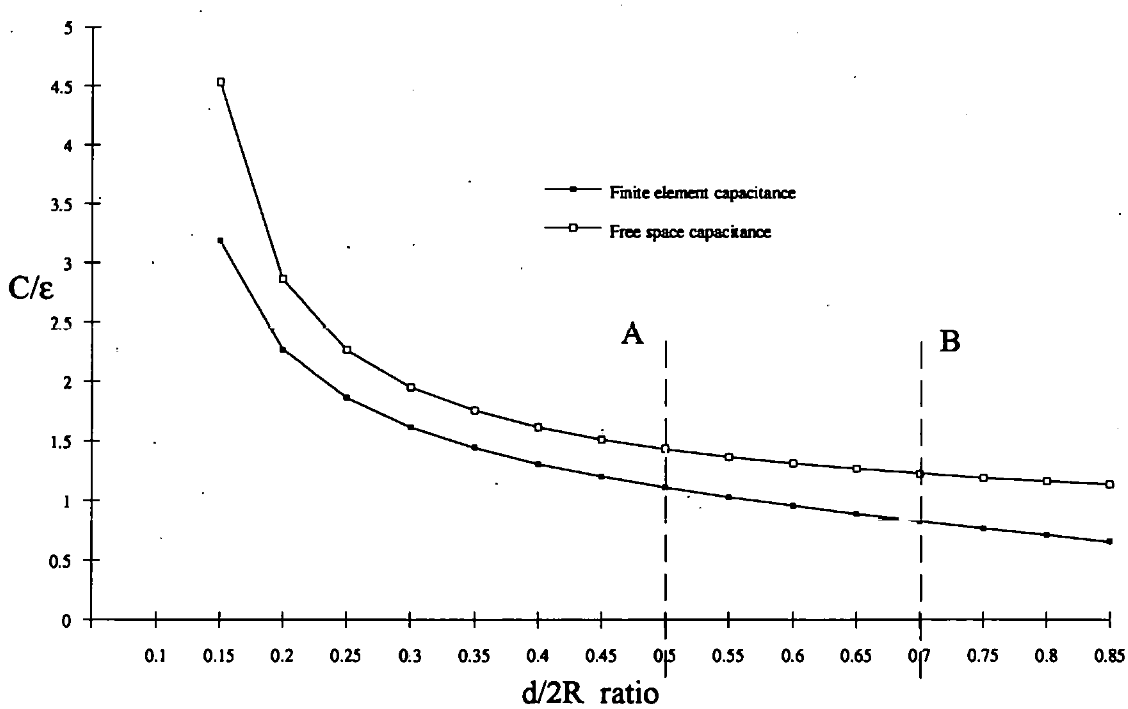

Figure 3.25. Calculated free space and experimental confined capacitance.

In the physical construction of three phase cables the conductors are normally within the points marked 'A' and 'B' on figure 3.25. Taking this data and applying regression methods as before yields the following equation.

$$C = 2.232 \times \varepsilon \times e^{-\left[\frac{1.483d}{2R}\right]} \tag{54}$$

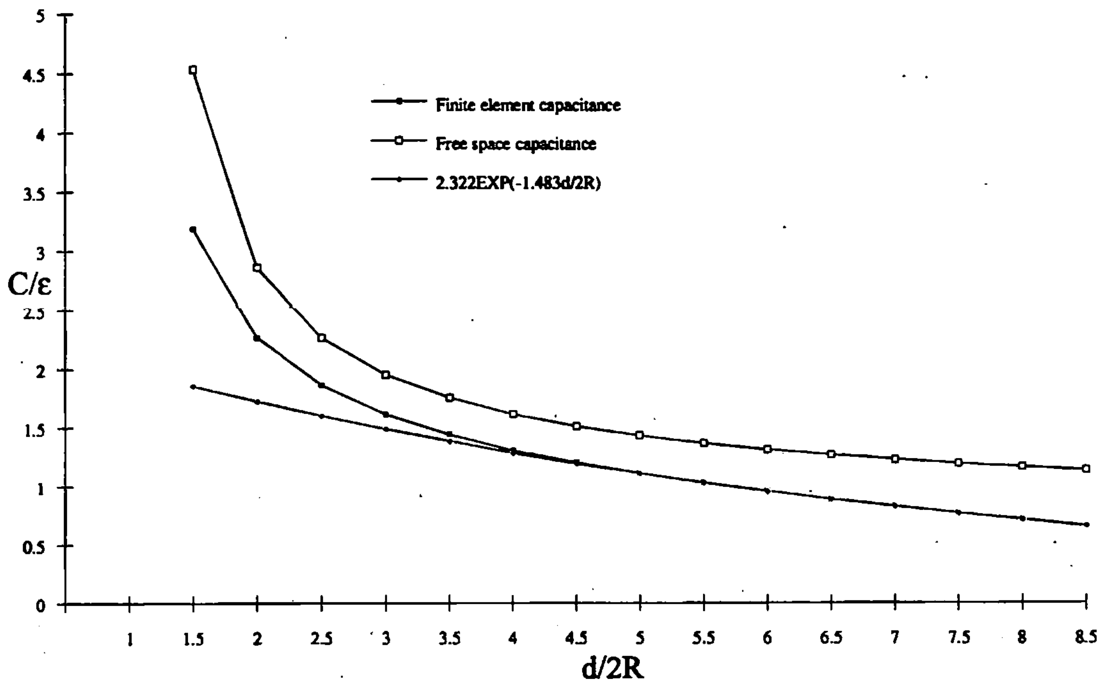

Figure 3.26. Plot showing the fit of the exponential to the measured data.

Within the range required the exponential gives a good fit to the experimental data. This was repeated with several different core sizes to give table 3.5.

d/2R	r/R =0.05	r/R = 0.1	r/R = 0.15	r/R = 0.2
0.1	2.3147			
0.15	1.7143	3.1888		
0.2	1.4597	2.2689		
0.25	1.2809	1.8645		
0.3	1.167	1.6153		2.7771
0.35	1.0627	1.4417	1.7812	2.2608
0.4	0.9963	1.3017	1.5799	1.9374
0.45	0.9248	1.1987	1.4233	1.7035
0.5	0.8726	1.1055	1.2968	1.5259
0.55	0.8175	1.0268	1.1893	1.381
0.6	0.7712	0.9529	1.0957	1.2605
0.65	0.7272	0.8871	1.0126	1.1553
0.7	0.6815	0.8261	0.9364	1.0644
0.75	0.6398	0.7666		
0.8	0.592	0.7083		
0.85	0.5478	0.6543		
0.9	0.4942			

Table 3.5. Experimental data for various core sizes and various core separations.

Using the regression methods described earlier, the following equation describes fully the capacitance between two parallel cylinders inside a circular parallel shield of length one metre.

$$C = \varepsilon \times 1.382 \times e^{\left[5.051\left[\frac{r}{R}\right]-\left[12.138\times\left[\frac{r}{R}\right]^{2}+1.340\right]\times\frac{d}{2\times R}\right]} \tag{55}$$

3.6 Core to Shield Capacitance

An equation for the capacitance between core and shield can be found using the same methods as follows.

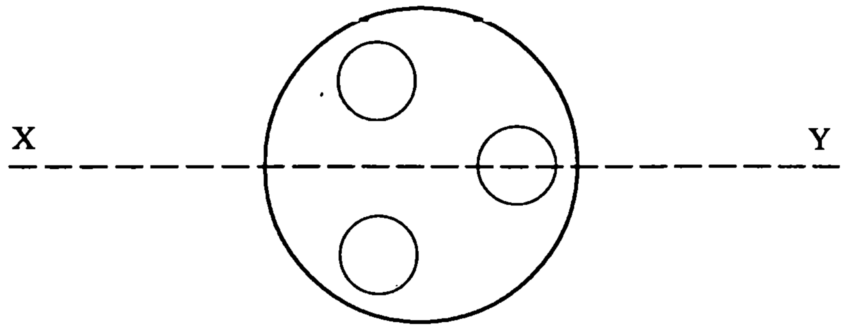

Figure 3.27. Diagram showing initial model for core-shield capacitance.

The symmetry of the problem will allow the analysis to be performed on half of the complete model.

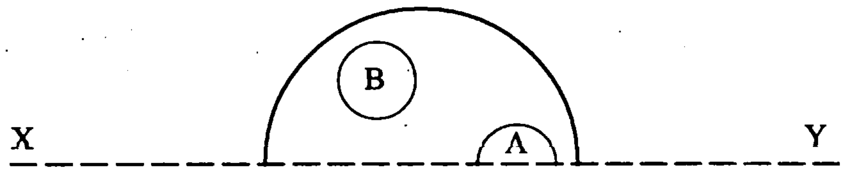

Figure 3.28. Diagram of half the initial model for core-shield capacitance.

Because of the limitation of the finite element software it is not possible to have conductor 'B' as a floating element while using conductor 'A' and the screen for the modelling. For this reason the model used was as in figure 3.29 with the core to core capacitance being subtracted from the result.

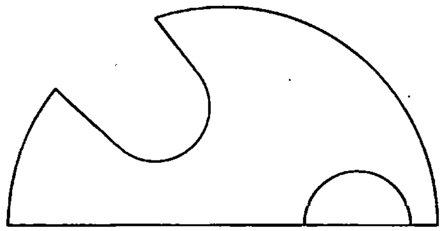

Figure 3.29. Diagram showing ideal model for core-shield capacitance.

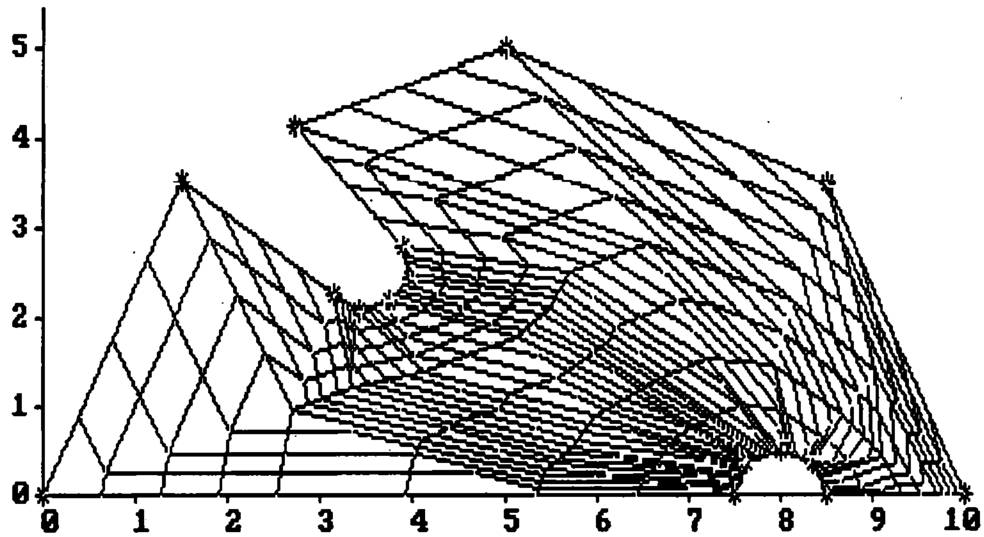

Figure 3.30. Specimen of finite element model showing r = 0.5 and R = 5.

For modern cables where the core centre is 0.536R the extraction of an equation for core/screen capacitance can be achieved by fixing the core position and varying the core size, as for the core/core capacitance. This method gave the results shown in table 3.6.

r/R	Finite element capacitance. 'C'
0.1	3.2914
0.15	4.3206
0.2	5.513
0.25	7.1692
0.3	9.3526
0.35	13.1188

Table 3.6. Experimental core/core+screen capacitance for various core sizes.

The results given in table 3.6 are for the capacitance between one core and the other core plus the screen (see figure 3.29). Subtracting the core to core capacitance and applying the regression methods to second and fourth order quadratics gives the results in table 3.7.

r/R	Finite element capacitance. 'C'	'C' - 'C' between cores.	Calculated 'C', 2nd order	Calculated 'C', 4th order
0.1	3.2914			
0.15	4.3206	3.0981	3.1896	3.0981
0.2	5.513	4.0951	3.9384	4.0951
0.25	7.1692	5.5149	5.4361	5.5149
0.3	9.3526	7.4209	7.6827	7.4209
0.35	13.1188	10.7958	10.6781	10.7958

Table 3.7. Experimental and Calculated capacitance for core to screen.

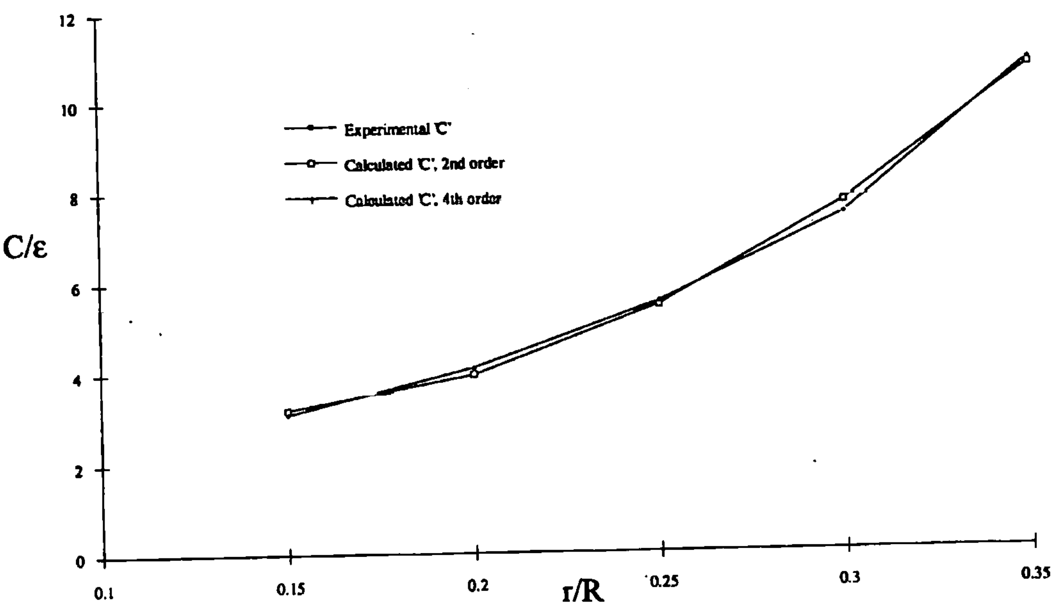

Figure 3.31. Plot showing the fit of the experimental to the calculated data.

Below are the second and fourth order polynomials used to produce table 3.7 and figure 3.31.

$$\frac{C}{\varepsilon}=149.8\times\left[\frac{r}{R}\right]^2-37.44\times\frac{r}{R}+5.44 \text{ and} \tag{56}$$

$$\frac{C}{\varepsilon}=61286\times\left[\frac{r}{R}\right]^4-54313\times\left[\frac{r}{R}\right]^3+1857.1\times\left[\frac{r}{R}\right]^2-2617\times\frac{r}{R}+15.80 \tag{57}$$

For modern three phase cables r/R is between 0.3 and 0.35. In this region the second order polynomial provides a good fit and is easy to implement. If greater accuracy is required the fourth order lies exactly on top of the experimental results.

If the core centre is not fixed at 0.536R then tables of data must be obtained for various core sizes and various conductor centres as follows.

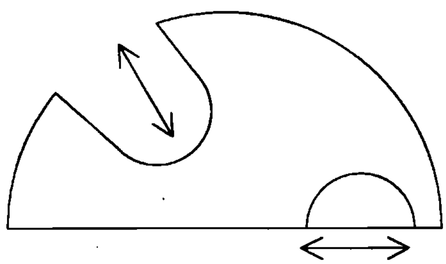

Figure 3.32.

Finite element model showing changes required for each position and core size.

The data given in table 3.8 can be matched with reasonable accuracy by using equation 55 added to the conformal transformation (equation 45) for non-concentric cylinders.

d/2R	r/R =0.05	r/R = 0.1	r/R = 0.15	r/R = 0.2
0.1	2.3147			
0.15	1.7143	3.1888		
0.2	1.4597	2.2689		
0.25	1.2809	1.8645		
0.3	1.167	1.6153		2.7771
0.35	1.0627	1.4417	1.7812	2.2608
0.4	0.9963	1.3017	1.5799	1.9374
0.45	0.9248	1.1987	1.4233	1.7035
0.5	0.8726	1.1055	1.2968	1.5259
0.55	0.8175	1.0268	1.1893	1.381
0.6	0.7712	0.9529	1.0957	1.2605
0.65	0.7272	0.8871	1.0126	1.1553
0.7	0.6815	0.8261	0.9364	1.0644
0.75	0.6398	0.7666		
0.8	0.592	0.7083		
0.85	0.5478	0.6543		
0.9	0.4942			

Table 3.8. Finite element results for various core sizes and position.

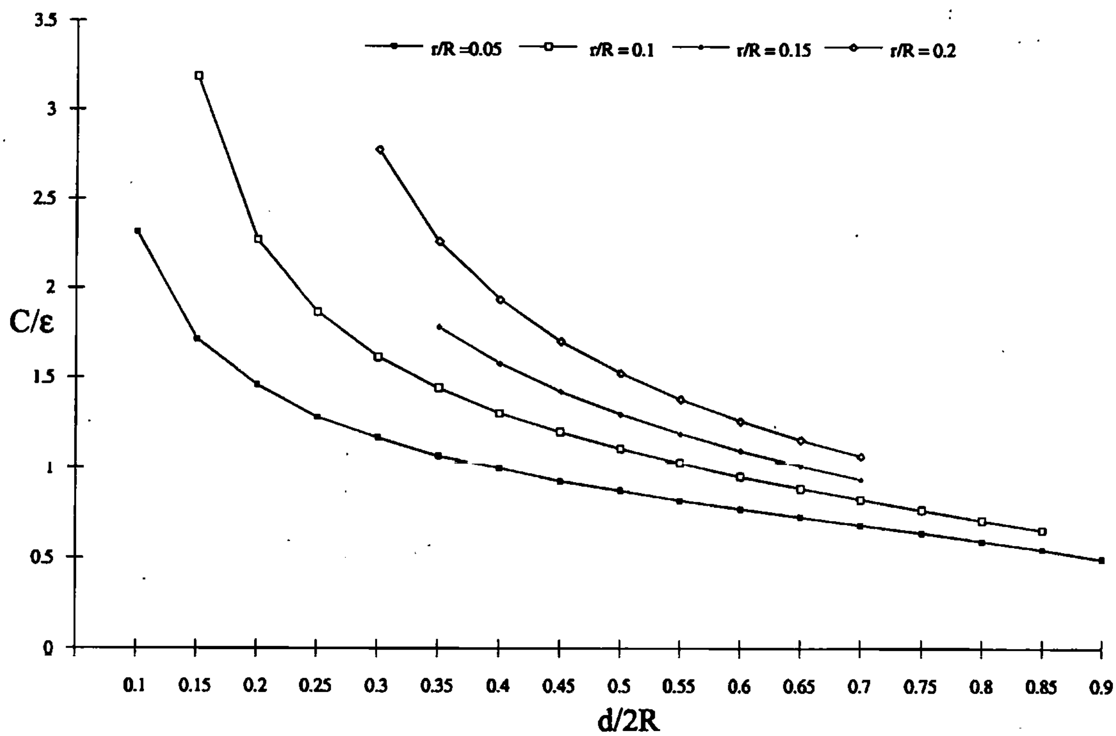

Figure 3.33. Graphical results of table 3.8.

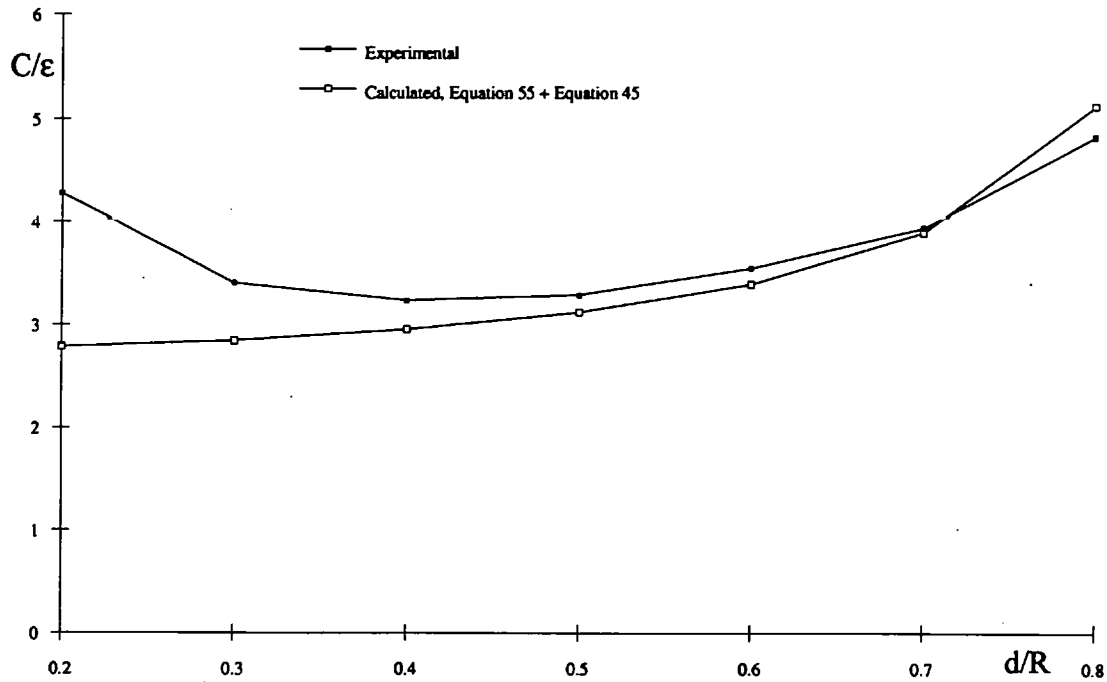

Figure 3.34. Comparison of results for a 0.5 core and 5 radius system.

Though the result from this method is not as accurate as the method for fixed centres the method is sufficiently accurate for the types of cable where it needs to be used. As these cables are older and no documentation is available for them the initial parameters used for the calculations can only be obtained by measurement of old samples and will therefore be less accurate. On the older type of cable the cable parameters will be more likely to change because of the materials used. This means that even if reasonable parameters can be obtained from a piece of old cable or from old documentation, there is no guarantee that the cable in the ground will have the same values because any slight faults on the cable allowing water ingress will, over time, result in cable parameter changes that are peculiar to that length of cable in that particular installation.

3.7 Non Circular Conductors

Values for capacitance and conductance of sector shaped conductors can be approximated with reasonable accuracy as follows :

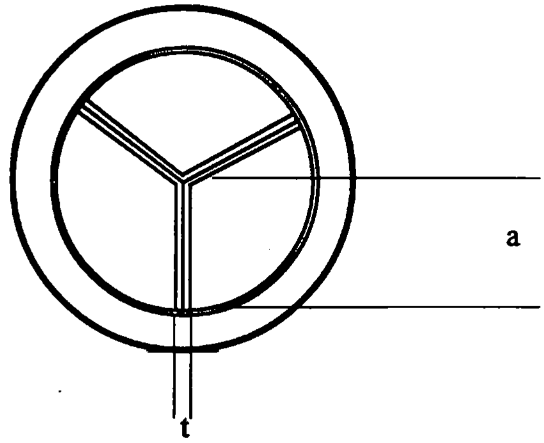

Figure 3.35. Segmented conductor cable

Treat the capacitance between conductors as the capacitance of two parallel plates of width 'a', length one metre and distance apart 't'.

Giving : $C = \frac{\varepsilon a}{t}$ farads per metre. (58a)

Conductance is given by $G = \frac{\sigma a}{t}$ siemens per metre. (58b)

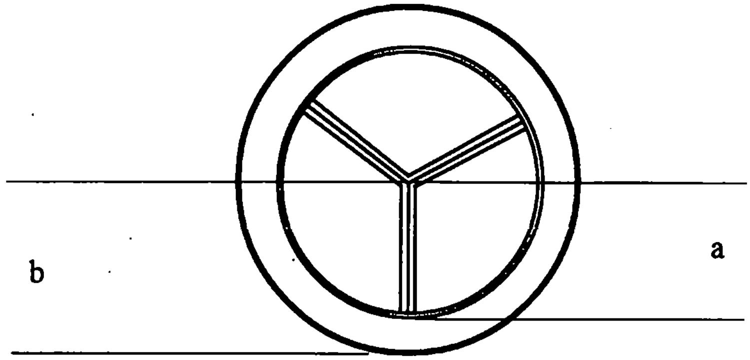

Figure 3.36. Segmented conductor cable showing inner and outer radii

Treat the capacitance between each core and shield as one third of the capacitance between concentric conductors, core of radius ‘a’ and shield of radius ‘b’ see figure 3.36 giving :-

$$C = \frac{2 \times \pi \times \varepsilon}{3 \times \ln \frac{b}{a}} \tag{59}$$

The accuracy of this approximation for sector shaped conductors can be checked using finite element analysis as follows. Consider the ½ sector shown in figure 3.37.

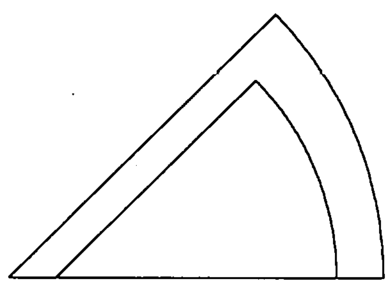

Figure 3.37. Half sector conductor

This represents half of a 90° sector of outside radius 10 units and sector radius 8 units. Using finite element techniques the capacitance of this system can be approximated to 17.29ε, this gives the total capacitance as 2×17.29ε = 34.58ε. The capacitance between two parallel plates with a length/separation ratio of 10 to 1, is 10ε, leaving the capacitance between conductor and screen, of 1 sector as 14.6ε. Using equation 44 the capacitance of two concentric circles of radii 10 and 9 can be calculated to be 59.6ε, a quarter of this is 14.9ε. This is very close to the capacitance calculated by finite elements

3.8 Waveform Cable

As the cable size increases the cable becomes physically more difficult to handle. To facilitate the bending and jointing on some of the heavier cables the shield is constructed as shown in figure 3.38 where the screen is laid on the core insulation in a sine wave. This increases the effective length of the shield, increasing resistance, the effect on the capacitance, inductance and conductance of the cable is minimal.

The increase in length of the shield can be calculated using calculus from the formula for the length of a curve [Ref. 13]

$$L = \int_a^b \sqrt{(1+\left[\frac{dy}{dx}\right]^2)}dx \tag{60}$$

Where: $a = 0$, $b = \frac{P}{2}$ and $y = \frac{A}{2} \times \sin\left[\frac{2\pi x}{P}\right]$

This gives the length for half a sine wave. The result must be multiplied by 2 and divided by 'P' to give a 'length increase ratio'.

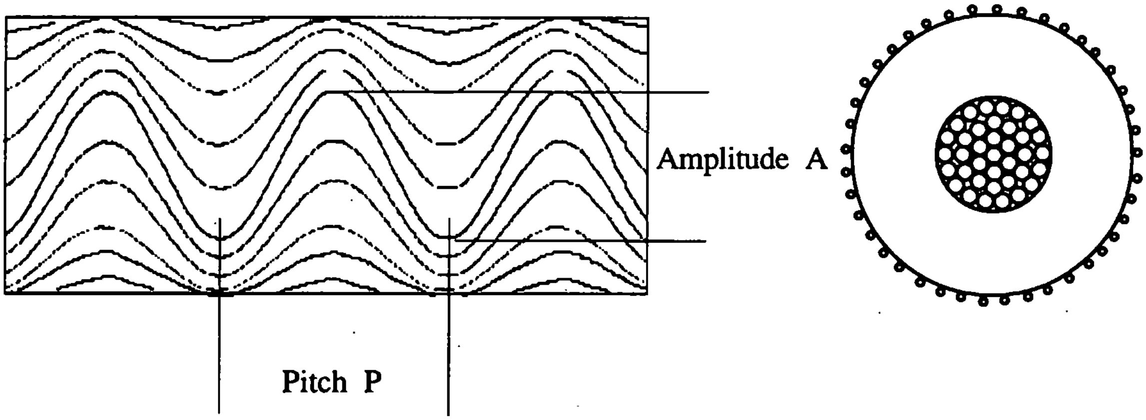

Figure 3.38. Example of stranded shield construction on some cables.

The length of these screen conductors can be calculated using equation 60. Cables constructed as shown are becoming more common. This is because of the increased bending ability but more importantly because, during the construction of a joint it is possible to 'expand' the shield, make the core joint within the expanded shield and seal the joint without cutting the shield conductors. This makes joints safer, with lower resistance, easier and quicker to construct, and more reliable.

The only significant effect of the sinusoidal construction of the screen is an increase in the resistance of the cable. The effect on other cable parameters is negligible.

Using normal cable construction the screen is wound helically round the core insulation. This process adds approximately 2% to the length of the screen conductors.

3.9 Resistance

3.9.1 Skin Effect

When current flows through a conductor there are internal flux linkages. Therefore current at the centre of the conductor will link more flux than current at the surface. This has the effect of increasing the value of inductance at the centre of the conductor. If the current is alternating the increased inductive reactance of the centre section causes current to migrate towards the surface giving an effective decrease in the cross sectional area of the conductor and increasing the resistance accordingly. As the frequency increases the effective cross sectional area decreases. This phenomena is termed the skin effect. At low frequency AC the effect can be ignored but at the frequencies of interest (1 to 10 MHz) skin effect (δ) must be accounted for if a reasonable model is to be formulated. [Ref. 14]

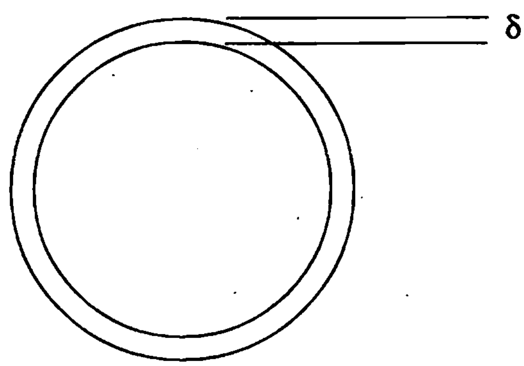

Figure 3.39. Skin effect in a round conductor.

The skin depth δ is a function of frequency and can be calculated using the equation 61. It is normal to assume that current density within the skin depth is uniform and that no current flows below the skin depth. In fact the current density varies throughout the material but the approximation made is sufficiently accurate for the needs of the research. [Ref. 14]

Skin depth (δ)

$$\delta=\sqrt{\frac{\rho}{\pi \times f \times \mu}} \tag{61}$$

In order to calculate the effective cross sectional area of a circular core conductor the area of the core diameter minus skin depth must be subtracted from the area of the core.

The effective area of the core becomes:

Effective cross sectional area = $\pi \times \text{radius}^2 - \pi \times (\text{radius}-\delta)^2$

The effective area of the screen becomes:

Effective cross sectional area = $\pi \times (\text{inside radius}+\delta)^2 - \pi \times (\text{inside radius})^2$

When this reduced area is applied to the equation for resistance the result will only be accurate if the conductors are solid (not stranded).

If the conductors are stranded the resistance calculations using 'δ' for skin depth will treat the core as a solid copper bar. From figures 3.40 and 3.39 it can be seen that this value will not be accurate.

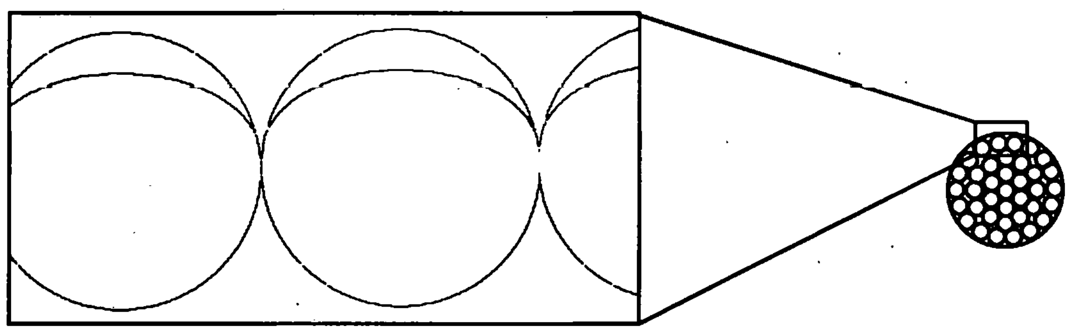

Figure 3.40. Magnified diagram of outer surface of stranded core showing approximate area of current flow.

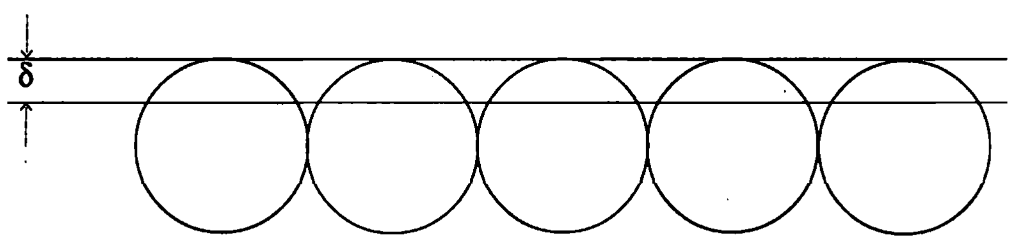

Figure 3.41. Magnified diagram of outer surface of stranded core showing calculated area of current flow

Calculations of the areas shown in figure 3.40 would be prohibitively complicated, an approximation can be used as shown below.

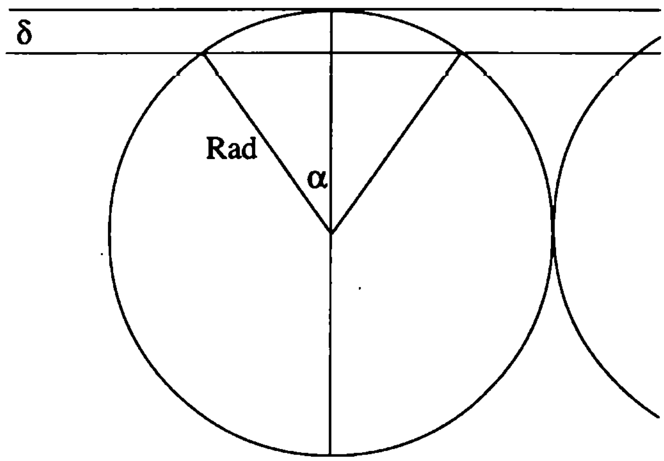

Figure 3.42. Single conductor of stranded core showing δ as calculated from the total cross sectional area of all cores..

$$\alpha = \mathrm{A}\cos\left[\frac{(\mathrm{Rad}-\delta)}{\mathrm{Rad}}\right] \tag{62}$$

$$\text{Effective area} = \alpha \times \mathrm{Rad}^2 - (\mathrm{Rad}-\delta)\sqrt{\mathrm{Rad}^2-(\mathrm{Rad}-\delta)^2} \tag{63}$$

$$\mathrm{Ratio} = \frac{\mathrm{Effective\_area}}{\mathrm{Total\_area}} = \frac{\mathrm{A}\cos\left[\frac{(\mathrm{Rad}-\delta}{\mathrm{Rad}}\right] \times \mathrm{Rad}^2 - (\mathrm{Rad}-\delta)\sqrt{\mathrm{Rad}^2-(\mathrm{Rad}-\alpha)^2}}{2\times\mathrm{Rad}\times\delta} \tag{64}$$

A more accurate value for resistance can now be calculated using the ratio to modify the area.

This calculation assumes the core diameter to be very large when compared to the core conductor diameter. The larger this ratio, the more accurate will be the approximation. A similar calculation can be applied to a stranded shield. On some stranded shield cables the conductors do not touch each other. In this case the distance between conductors compared to conductor radius must be measured and a decision made as to whether or not to account for a reduction in effective area as shown.

3.10 Inductance

From experimentation, calculation and known parameters for common communication cables (COAX), the inductance of cable constructed in this manner is very low and does not have significant effects on the communication capabilities of the system. [Ref. 10]

As all underground distribution cables have non magnetic conductors the relative permittivity is equal to absolute permittivity that is μ_r is taken as μ_0

3.10.1 Core to sheath inductance

In any system where one conductor is totally surrounded by another, the inductance between the two can be split into three separate parts. [Ref. 14]

1) Internal core flux linkage. This is due to the core flux linking a fraction of the core current. In the frequency range 1 MHz to 10 MHz this can be ignored because it is assumed that the skin effect causes the current to flow at the outer surface of the conductor leaving no flux in the conductor centre.

2) Core-sheath linkage. This is due to the core-sheath flux linking the total core current. This is the major contributor to the inductance in the system.

3) Sheath linkage. This is due to the sheath flux linking the core current plus a fraction of the sheath current. This value is minimal because as in '1' the return current flows along the inner surface of the sheath leaving no flux inside the sheath conductor.

For single phase concentric cables the inductance between core and shield is given by:

$$L = \frac{\mu_r}{2\pi} \ln \frac{b}{a} \tag{65}$$

where 'b' is the shield internal diameter and 'a' is the core diameter.

3.10.2 Three phase cable inductance

On three phase cables there are two inductances to consider. These are, the core to shield inductance and the core to core inductance. As the effect of inductance on the system is small, the values used have been calculated using the equations for concentric conductors and parallel conductors. These values are not totally accurate because of the cable construction but are simpler to use and understand. The actual values for inductance could be calculated using the same conformal trasformation methods that were used for the capacitance but it was felt that the effects of the errors introduced would be small when compared to other variables within the system.

3.10.3 Core to core inductance

The equation for inductance between two parallel conductors in free space is given by:

$$\mathrm{L} = \frac{\mu_r}{\pi} \ln \frac{\mathrm{b} - \mathrm{a}}{\mathrm{a}} \tag{66}$$

where 'b' is the distance between conductors and 'a' is the core diameter.

3.10.4 Core to sheath inductance

The core to sheath conductance was calculated using equation 65.

3.11 Applying Transmission Line Parameters to Transmission Line Equations.

From equation 20, impedance per unit length matrix

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \tag{67}$$

$Z_{ii} = R_{ii} + 2\times\pi\times f\times L_{ii}$

Where R_{ii} is the core resistance plus the screen resistance and L_{ii} is the inductance between core and screen.

$$Z_{ij} = 0 + 2\times\pi\times f\times L_{ij} \ (i\neq j) \tag{68}$$

Where L_{ij} is the inductance between cores.

From equation 21, admittance per unit length matrix

$$Y = \begin{bmatrix} Y_{11}+Y_{12}+Y_{13} & -Y_{12} & -Y_{13} \\ -Y_{21} & Y_{22}+Y_{21}+Y_{23} & -Y_{23} \\ -Y_{31} & -Y_{32} & Y_{33}+Y_{31}+Y_{32} \end{bmatrix} \tag{69}$$

$$Y_{ii} = G_{ii} + 2\times\pi\times f\times C_{ii} + 2\times Y_{ij} \tag{70}$$

Where G_{ii} is the conductance between core and screen and C_{ii} is the capacitance between core and screen.

$$Y_{ij} = G_{ij} + 2\times\pi\times f\times C_{ij} \ (i\neq j) \tag{71}$$

Where G_{ij} is the conductance between cores.

and C_{ij} is the capacitance between cores.

3.12 Summary

This chapter has covered all the equations and the implementation of those equations needed to approximate the transmission line response of power cables given their physical dimensions. Wherever possible the calculations involve known formulae. Where this was not possible, equations have been developed empirically that approximate, with sufficient accuracy, the parameter required.

Greater accuracy can be achieved with deeper analysis of the cable relationships, but it was felt that with the accuracy of the original data taken into account this would give no significant improvement in the accuracy of the final result.

The equations developed in this chapter allow the voltage and current at any point along a length of cable to be calculated. They provide the basic starting point in developing a method of calculating voltage and current at any point on electricity distribution networks, over a given frequency range. Because the application of these equations to distribution networks is repetative, involving hundreds of calculations even for a small network, the implementation of the equations is best achieved using a computer programme.

Chapter 4. Computer Programming

4.1 Introduction

Using the equations developed in chapter 3 a computer programme was written to calculate the attenuation between the substation and any customer termination point on the network. With this facility it is possible to allow certain discrete frequencies or frequency bands to be chosen where the attenuation between the substation and any supply point produced the required response. This will normally be required to be a minimum or may be chosen for a reasonably flat frequency versus attenuation response over a small frequency range. In order to provide a complete analysis, calculations need to be done to provide the response from the substation to any supply point and from any supply point to any other supply point. For simplicity the programming was limited to calculating the attenuation from the substation to the end of any of the spurs on the network and the impedance looking into any point on the network. This will prove that the methods applied are valid and incorporation of the spur to spur response can be added at some future time.

4.2 Transmission Line Parameters

Programming of the transmission line equations developed in chapter 3 for computer analysis was achieved using Borland Turbo C^{++} version 3.0 for Dos using the following methods.

The programme will only calculate the parameters of a network with single phase supplies fed from a single three phase main run, it cannot cater for any three phase supplies from the main three phase cable or multiple supplies from one substation. This limitation is introduced to simplify the finished programme in order that it be easier to understand. The addition of the facility for three phase supplies and multiple runs involves a more complicated implementation of the equations given but does not involve any further equations.

4.3 Single Phase Programming

The programming of the single phase transmission line equations was straightforward. A documented listing of the functions is included in the appendix 1.

4.4 Calculation of resistance(resistance())

The function is entered with frequency, cable material and cable dimensions and calculates the resistance by implementing equations 61 to 64 inclusive.

4.5 Calculation of capacitance(capacitance())

The function is entered with cable dimensions and cable insulator permittivity and calculates capacitance using equation 44.

4.6 Calculation of inductance

The calculation of inductance uses the value of capacitance already calculated. The calculation is not performed in a separate function but is done in the main programme. In the calculation μ_r is taken as μ_0.

4.7 Calculation of conductance(conductance())

The conductance of modern 'plastic' insulated cables is very high and very stable, both with age and temperature. The value of ρ is in the order of 10^{-16}. It can be calculated using equation 44, though the effect of the result on the network characteristic is minimal and this programme has been speeded up by fixing this value at 10^{-17} irrespective of cable dimensions. The functions to calculate conductance are included in the listings.

4.8 Gamma Calculation

This function implements equation 4. It is entered with 'R', 'L', 'G' and 'C' and returns gamma. This value is calculated within the function requiring it. This value is not available to the main programme but is used and calculated from within the 'Zin_single()' function.

4.9 Zo Calculation

This function is performed using equation 9. It is entered with 'R', 'L', 'G' and 'C' and returns with Zo. This value is not available to the main programme but is used and calculated from within the 'Zin_single()' function.

4.10 Impedance looking into line(Zin_single())

This function implements equation 19. Termination impedance is defined within the function, Zo and gamma are calculated within the function.

4.11 Single Phase Summary

This implementation of the single phase transmission line equations produces results that compare favourably with practical results carried out at NORWEB's Chorley test facility. A comparison between calculated and practical results for the single phase implementation is shown in figure 5.13.

4.12 Multi Phase Transmission Lines

The implementation of the three phase transmission line equations from chapter 3 is not as straightforward as the single phase because the matrix functions required are not included in the programming language. The following is an explanation of the matrix mathematics needed to accomplish computer calculations of three phase transmission lines.

The inverse of a matrix is not a stable entity and can in certain applications result in 'division by zero' errors. To overcome this problem the inverse is not used but an equivalent method is explained below.

Given the matrices $A=\begin{bmatrix} a_{00} & a_{01} & a_{02} \\ a_{10} & a_{11} & a_{12} \\ a_{20} & a_{21} & a_{22} \end{bmatrix}$, $B=\begin{bmatrix} b_{00} & b_{01} & b_{02} \\ b_{10} & b_{11} & b_{12} \\ b_{20} & b_{21} & b_{22} \end{bmatrix}$, $C=\begin{bmatrix} c_{00} & c_{01} & c_{02} \\ c_{10} & c_{11} & c_{12} \\ c_{20} & c_{21} & c_{22} \end{bmatrix}$ (67)

and that $B = A^{-1} \times C$, it follows that by pre-multiplying by 'A' gives $A \times B = C$ In this equation, 'B' is the unknown matrix.

By standard matrix multiplication, if the 'A' matrix is an upper triangular matrix (0 below the leading diagonal) then:

(68) (69) (70) (71) (71) (72)

$a_{22}\times b_{20}=c_{20}$, $a_{22}\times b_{21}=c_{21}$, $a_{22}\times b_{22}=c_{22}$ therefore $b_{20}=\frac{c_{20}}{a_{22}}$, $b_{21}=\frac{c_{21}}{a_{22}}$ and $b_{22}=\frac{c_{22}}{a_{22}}$

(73) (74) (75)

Similarly: $b_{10}=\frac{c_{10}-a_{12}\times b_{20}}{a_{11}}$, $b_{11}=\frac{c_{11}-a_{12}\times b_{21}}{a_{11}}$ and $b_{12}=\frac{c_{12}-a_{12}\times b_{22}}{a_{11}}$

(76) (77)

and: $b_{00}=\frac{c_{00}-a_{01}\times b_{10}-a_{02}\times b_{20}}{a_{00}}$, $b_{01}=\frac{c_{01}-a_{01}\times b_{11}-a_{02}\times b_{21}}{a_{00}}$,

(78)

$$b_{02}=\frac{c_{02}-a_{01}\times b_{12}-a_{02}\times b_{22}}{a_{00}}.$$

These calculations are further simplified if a_{00} and a_{11} are equal to 1. The required 'A' matrix is therefore:

$$newA = \begin{bmatrix} 1 & na_{01} & na_{02} \\ 0 & 1 & na_{12} \\ 0 & 0 & na_{22} \end{bmatrix} \tag{79}$$

This can be achieved by using matrix manipulation on 'A' with any changes applied to 'C' in order to maintain the equality, as shown below.

In order to make $na_{10} = na_{20} = na_{21} = 0$ and $na_{00} = na_{11} = 1$, the following must be applied to obtain the na_{01}, na_{02}, na_{12} and na_{22} terms where na_{xx} represents the 'new A' matrix elements.

$$na_{01} = \frac{a_{01}}{a_{00}} \tag{80}$$

$$na_{02} = \frac{a_{02}}{a_{00}} \tag{81}$$

$$na_{12} = \frac{a_{12} - \dfrac{a_{10} \times a_{02}}{a_{00}}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}} \tag{82}$$

$$na_{22} = a_{22} - \frac{a_{20} \times a_{02}}{a_{00}} - na_{12} \times a_{21} - \frac{a_{20} \times a_{01}}{a_{00}} \tag{83}$$

These modifications must also be applied to the 'C' matrix to give the 'new C' matrix as follows.

$$\overset{(84)}{nc_{00} = \frac{c_{00}}{a_{00}}}, \quad \overset{(85)}{nc_{01} = \frac{c_{01}}{a_{00}}} \text{ and } \overset{(86)}{nc_{02} = \frac{c_{02}}{a_{00}}}$$

$$\underset{(87)}{nc_{10} = \frac{c_{10} - a_{10} \times nc_{00}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}}}, \quad \underset{(88)}{nc_{11} = \frac{c_{11} - a_{10} \times nc_{01}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}}} \text{ and } \underset{(89)}{nc_{12} = \frac{c_{12} - a_{10} \times nc_{02}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}}}$$

$$nc_{20} = c_{20} - a_{20} \times nc_{00} - \frac{a_{21} - \dfrac{a_{20} \times a_{01}}{a_{00}}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}} \times \frac{c_{10} - a_{10} \times c_{00}}{a_{00}} \tag{90}$$

$$nc_{21} = c_{21} - a_{20} \times nc_{01} - \frac{a_{21} - \dfrac{a_{20} \times a_{01}}{a_{00}}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}} \times \frac{c_{11} - a_{10} \times c_{01}}{a_{00}} \tag{91}$$

$$nc_{22} = c_{22} - a_{20} \times nc_{02} - \frac{a_{21} - \dfrac{a_{20} \times a_{01}}{a_{00}}}{a_{11} - \dfrac{a_{10} \times a_{01}}{a_{00}}} \times \frac{c_{12} - a_{10} \times c_{02}}{a_{00}} \tag{92}$$

This gives the matrices:

$$newA = \begin{bmatrix} 1 & na_{01} & na_{02} \\ 0 & 1 & na_{12} \\ 0 & 0 & na_{22} \end{bmatrix}, \quad B = \begin{bmatrix} b_{00} & b_{01} & b_{02} \\ b_{10} & b_{11} & b_{12} \\ b_{20} & b_{21} & b_{22} \end{bmatrix}, \quad newC = \begin{bmatrix} nc_{00} & nc_{01} & nc_{02} \\ nc_{10} & nc_{11} & nc_{12} \\ nc_{20} & nc_{21} & nc_{22} \end{bmatrix}$$

and the solutions for the unknown 'B' matrix are:

$$b_{20} = \frac{nc_{20}}{na_{22}}, \ (93) \qquad b_{21} = \frac{nc_{21}}{na_{22}}, \ (94) \qquad b_{22} = \frac{nc_{22}}{na_{22}}, \ (95)$$

$$b_{10} = \frac{nc_{10} - na_{12} \times b_{20}}{na_{11}}, \ (96) \qquad b_{11} = \frac{nc_{11} - na_{12} \times b_{21}}{na_{11}}, \ (97)$$

$$b_{12} = \frac{nc_{12} - na_{12} \times b_{22}}{na_{11}}, \ (98) \qquad b_{00} = \frac{nc_{00} - na_{01} \times b_{10} - na_{02} \times b_{20}}{na_{00}}, \ (99)$$

$$b_{01} = \frac{nc_{01} - na_{01} \times b_{11} - na_{02} \times b_{21}}{na_{00}}, \ (100) \qquad b_{02} = \frac{nc_{02} - na_{01} \times b_{12} - na_{02} \times b_{22}}{na_{00}}. \ (101)$$

This method removes the need to invert the 'A' matrix thereby providing a stable solution to the problem. However in certain matrices applying this method can result in the na_{22} element being zero. If this is the case the method will not work. The solution is to swap the first and second rows of the 'A' and 'C' matrices before applying the method. This can be done without invalidating the equality of the equation. If the na_{22} element is still zero the method must be repeated with the first and third rows of the 'A' and 'C' matrices swapped and so on until a valid solution is found.

This method can also be applied to find the solution to the problem $B = C \times A^{-1}$, in this case 'B' is post multiplied by 'A' to give $B \times A = C$. The 'A' matrix is again transformed into an upper triangular matrix with any modifications applied to 'C'. This solution differs in the way that the final values for 'B' are calculated. With this solution if a zero is found in element na_{22} columns instead of rows are swapped. If this is necessary, the columns of the solution matrix will also need swapping, unlike the previous case.

4.13 Three Phase Programming

The programming of the three phase transmission line equations is developed in the following sections. A documented listing of the functions is included in the appendices.

For programming purposes the conductor centre on the three phase cables is fixed at 0.536 of the screen radius, that is, the programme will only calculate the network response of modern cables. The inclusion of the ability to calculate parameters for older networks can be achieved using the relevant equations.

4.14 Calculation of resistance(resistance())

This function is the same function as for single phase. It is entered with frequency, cable material and cable dimensions and calculates the resistance by implementing equations 61 to 64.

4.15 Calculation of capacitance

(cre_cre_3_capacitance())

Core to core capacitance. The function is entered with cable dimensions and cable insulator permittivity and calculates capacitance using equation 52.

(cre_she_3_capacitance())

Core to shield capacitance. The function is entered with core to core capacitance, cable dimensions and cable insulator permittivity and calculates capacitance using equation 56.

4.16 Calculation of inductance

The calculation of inductance uses equation 65. The calculation is not performed in a separate function but is done in the main programme.

4.17 Calculation of conductance
(cre_cre_3_conductance())

Core to core conductance. The function is entered with cable dimensions and cable insulator conductivity and calculates conductance using equation 52.

(cre_she_3_conductance())

Core to shield conductance. The function is entered with core to core capacitance, cable dimensions and cable insulator conductivity and calculates conductance using equation 56.

4.18 Impedance looking into the network from any point(Zin_three())

This function implements equation 29. Termination impedance is calculated prior to entry (Zterm), Z_0 and gamma are calculated within the function using length, frequency and cable parameters, final calculation of the three by three impedance matrix is performed by calling the function Zmatrix with all necessary components calculated. The function returns a 3x3 matrix in the array 'Zmat'.

4.19 Voltage looking into the network from any point(Vin_three())

This function implements equation 30. Impedance at either end of the length of cable is known, as is the voltage at the sending end. The function calls 'Vmatrix' after calculating the parameters needed. The function returns a 3x1 matrix containing the voltages at the end of the length of cable.

4.20 Method of calculation

In the network shown in figure 4.1. Each of the spurs 'A' to 'D' is terminated with 50 ohms. The impedance looking into each of the spurs is calculated using single phase theory. This reduces the network as shown in figure 4.2.

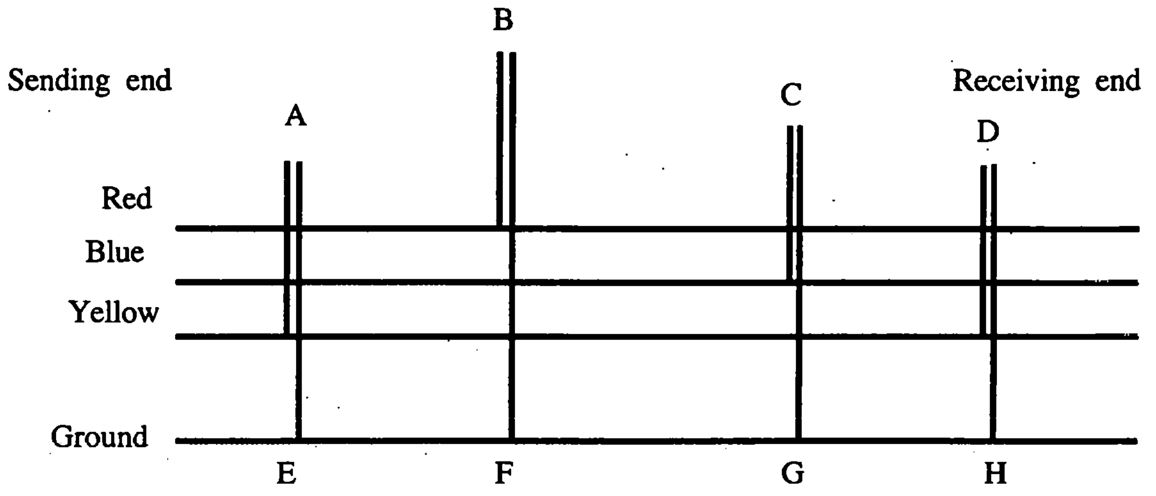

Figure 4.1. Three phase network

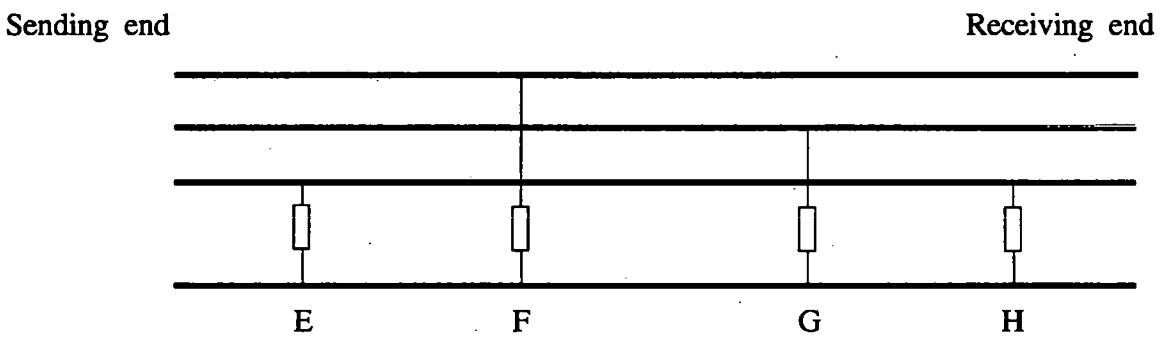

Figure 4.2. First reduction of three phase network

From point 'H' the impedance can be calculated looking towards the receiving end using multi phase theory to return a 3x3 impedance matrix.

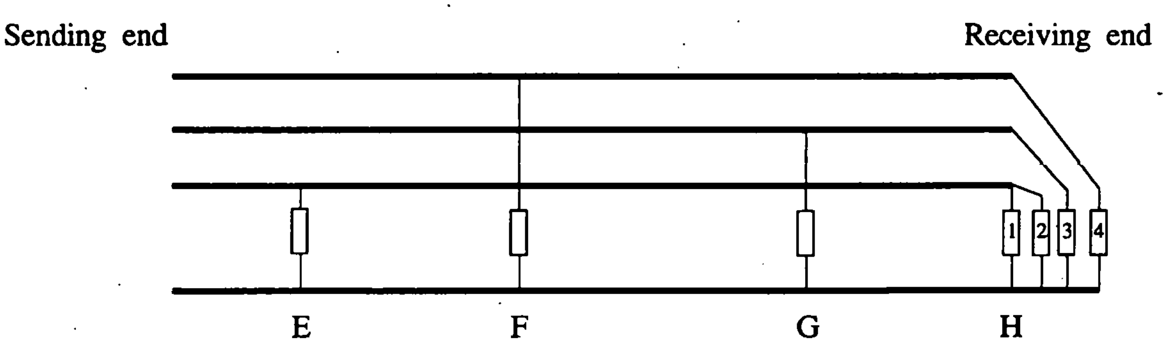

Figure 4.3. Second reduction of three phase network

The impedance looking into the 'H' spur (1) is paralleled with the appropriate value within this 3x3 matrix (2) to give an equivalent termination matrix at the point 'H'. The process is repeated calculating the impedances moving towards the sending end until no cable lengths remain, leaving a 3x3 matrix at the sending end representing the impedance looking into the line. The impedance looking towards the sending end is calculated in a similar manner working towards the receiving end to give a series of 3x3 impedances at all spur connection points looking towards the source.

With the value for impedance looking into the network the voltages at the source/network boundary can now be calculated.

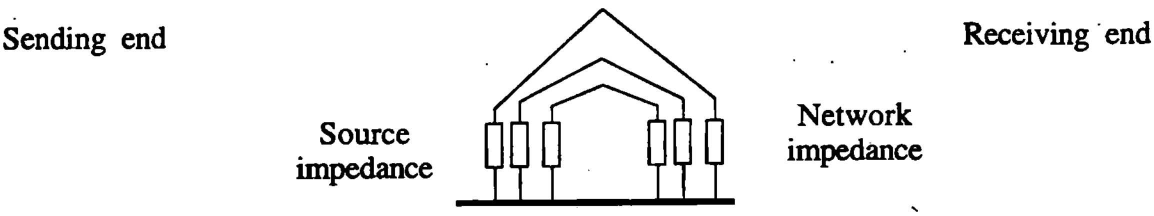

Figure 4.4. Final reduction of three phase network

With the source voltage matrix and the source impedance matrix at the source network boundary, the impedance looking towards the receiving end from 'E' and the parameters of the three phase cable connecting the source to 'E', another voltage matrix can be calculated for the network at the point 'E'.

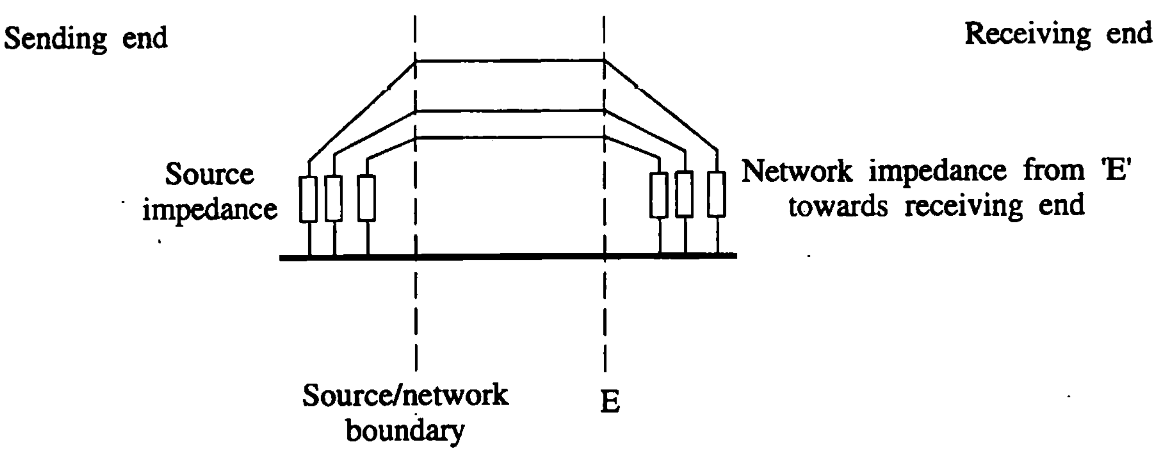

Figure 4.5. Equivalent circuit for calculation of voltage matrix at 'E'.

This can be repeated to give a voltage matrix for each of the joints on the main three phase cable. Using the relevant voltage matrix element as the source voltage for the relevant spur, a value for the voltage at the termination of any of the spurs can be calculated.

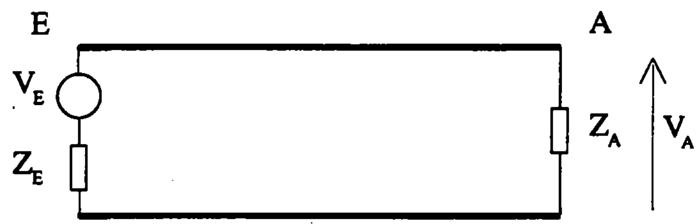

Figure 4.6. Equivalent circuit for calculation of output voltage.

Z_E is the impedance looking towards the source in parallel with the impedance looking towards the receiving end.

Z_A is the terminating impedance of the spur, set at 50 ohms by the software.

V_A is the unknown output voltage.

4.21 Data entry.

The entry of the physical data relating to a network involves entering cable lengths and dimensions for each spur and for each piece of three phase main cable. Because this data is fixed for a particular network and analysis may be required with different termination/source impedances or frequencies, the network entry is performed in a separate programme with the data being stored to disk. This data file is opened by the analysis programme and calculations are performed before the result is stored to disk.

Initially the user is asked for the number of spurs on the network. Once this is known the PC will switch into graphics mode and draw a single horizontal line with this number of spurs vertically off it. The sending end of the network is assigned the letter 'A' and each spur will be assigned consecutive letters from the sending end. The user is then asked for the phase colour and length of each of the spurs. The vertical line representing the spur will change to the appropriate colour and the length is printed on the side of the spur. See figure 4.7.

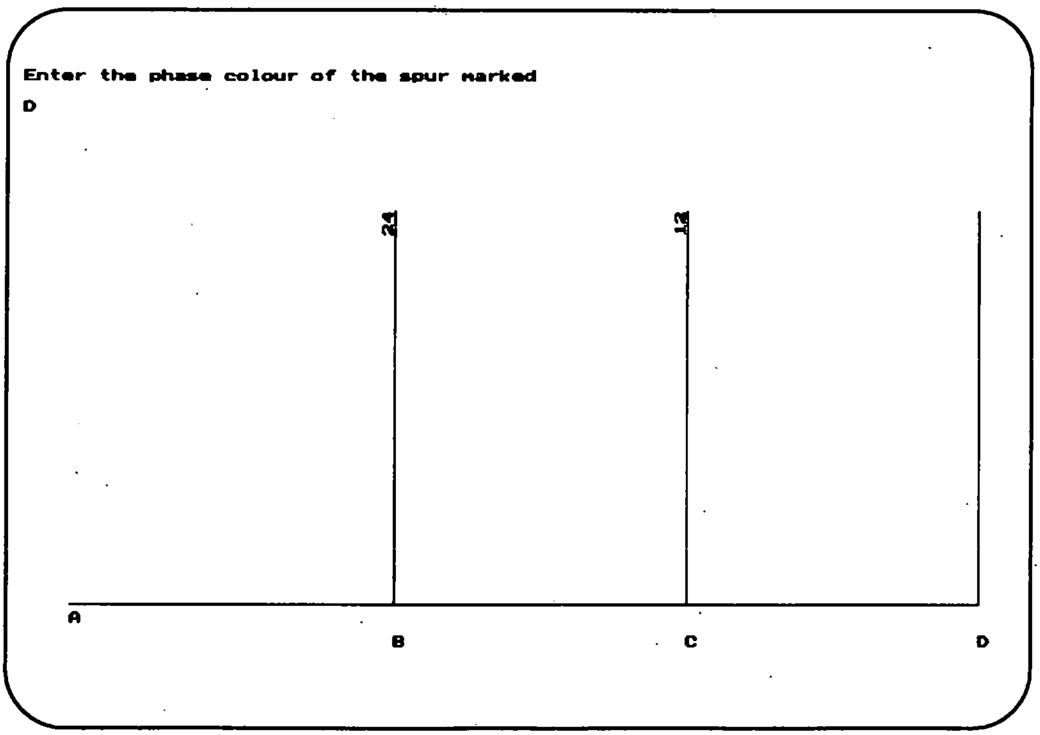

Figure 4.7. Sample data entry screen with three spurs.

The questions are repeated for the lengths of three phase cable between the spurs and for all the relevant information needed to calculate the transmission line parameters of all the sections of cable. For a 25 spur network this is approximately 500 pieces of information. This information is stored using the format shown below. The example is for the three feed network shown in figure 4.7.

```
Feeds
3
Spurlengths
2.400000e+01 0.000000e+00 0.000000e+00
0.000000e+00 0.000000e+00 1.000000e+01
0.000000e+00 1.200000e+01 0.000000e+00
Mainlengths
1.200000e+01 1.300000e+01 1.400000e+01
Spur core diameter
2.500000e+01 2.500000e+01 2.000000e+01
Spur shield diameter
4.000000e+01 4.000000e+01 3.500000e+01
Spur core material
C C C
Spur shield material
C C C
Spur core strand diameter
3.000000e+00 0.000000e+00 0.000000e+00
Spur shield strand diameter
2.000000e+00 0.000000e+00 0.000000e+00
Spur permeability
3.000000e+00 3.000000e+00 4.000000e+00
Main conductor type
S S C
Main core diameter
2.200000e+01 2.200000e+01 2.200000e+01
Main screen diameter
4.000000e+01 4.000000e+01 4.500000e+01
Main core conductor material
C C C
Main screen conductor material
C C A
Main core strand diameter
1.000000e+00 0.000000e+00 1.000000e+01
Main shield strand diameter
0.000000e+00 0.000000e+00 0.000000e+00
Main permeability
2.200000e+00 3.320000e+00 1.560000e+00
```

Figure 4.8. Sample data file for three spur network.

The data file uses ASCII text with no formatting other than a carriage return (0D hex) at the end of each line and a space (20 hex) between each file entry. The statements within the data file must remain unchanged but the values can be edited with a standard ASCII text editor if required. Only copper or aluminium is allowed for the conductor material. The data file can be broken down as follows.

Number of spurs running off the main three phase cable.

Feeds

3

The lengths of each of the spurs, if the value is 0 then the spur is not connected to that phase. The phase order is red, blue and yellow. This example has, from the sending end, a 24 metre spur on red, a 12 metre spur on yellow and a 10 metre spur on blue.

Spurlengths

2.400000e+01 0.000000e+00 0.000000e+00

0.000000e+00 0.000000e+00 1.000000e+01

0.000000e+00 1.200000e+01 0.000000e+00

The lengths of three phase cable between, sending end and first spur (12 metres), first spur and second spur (13 metres) and between the second and third spurs (14 metres)

Mainlengths

1.200000e+01 1.300000e+01 1.400000e+01

Central conductor diameter of the spurs in mm

Spur core diameter

2.500000e+01 2.500000e+01 2.000000e+01

Shield conductor internal diameter of the spurs in mm

Spur shield diameter

4.000000e+01 4.000000e+01 3.500000e+01

Central conductor and shield conductor material, C = copper, A = aluminium

Spur core material

C C C

Spur shield material

C C C

Diameter in mm of each strand within core/shield (0 if not stranded)

Spur core strand diameter

3.000000e+00 0.000000e+00 0.000000e+00

Spur shield strand diameter

2.000000e+00 0.000000e+00 0.000000e+00

Relative permeability of insulating material

Spur permeability

3.000000e+00 3.000000e+00 4.000000e+00

Three phase conductor type, 'S' for segmented cores and 'C' for circular cores.

Main conductor type

S S C

Repeated for three phase cable lengths.

Main core diameter

2.200000e+01 2.200000e+01 2.200000e+01

Main screen diameter

4.000000e+01 4.000000e+01 4.500000e+01

Main core conductor material

C C C

Main core strand diameter

1.000000e+00 0.000000e+00 1.000000e+01

Main shield strand diameter

0.000000e+00 0.000000e+00 0.000000e+00

Main screen conductor material

C C A

Main permeability

2.200000e+00 3.320000e+00 1.560000e+00

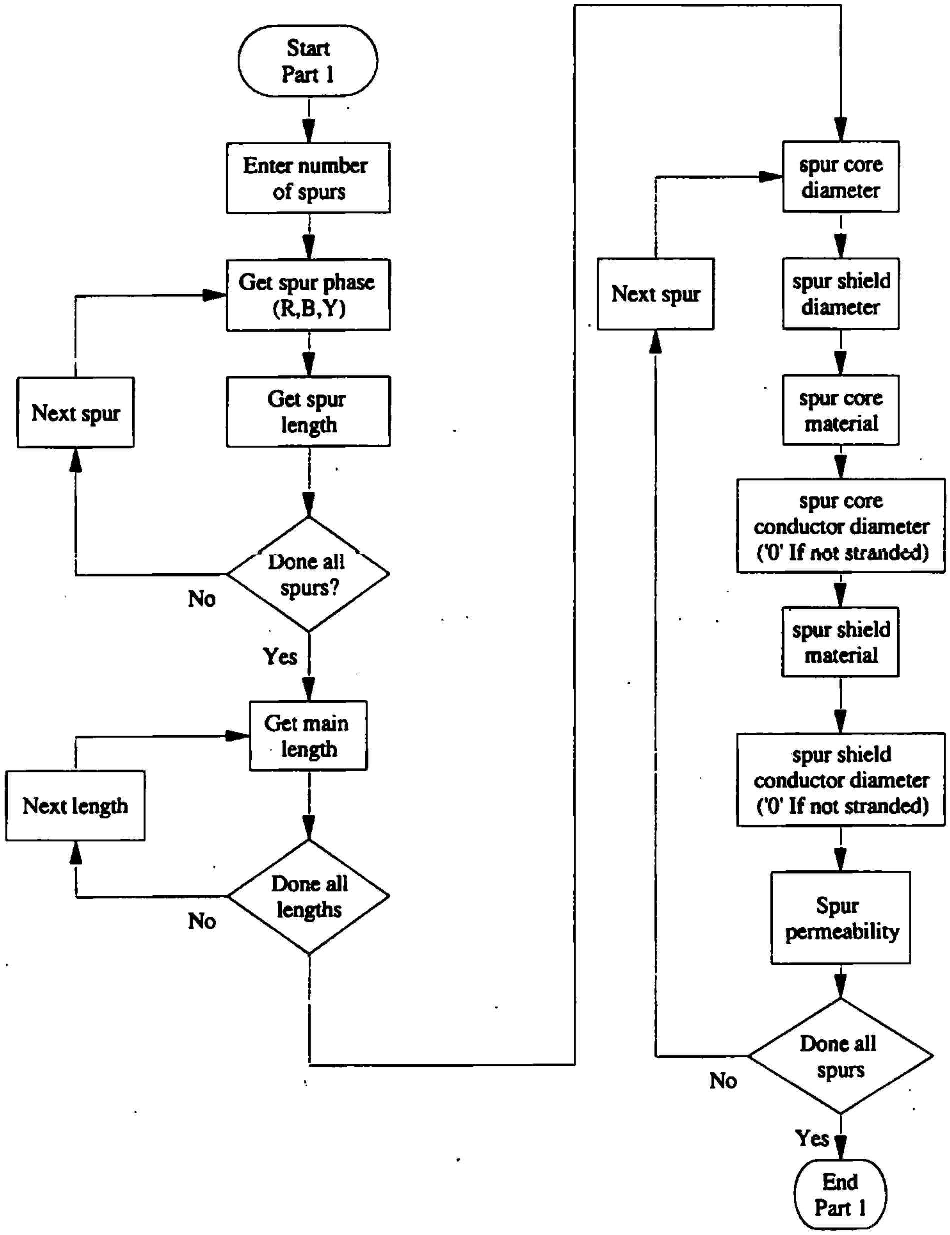

Figure 4.9.a Flow chart for entering network data

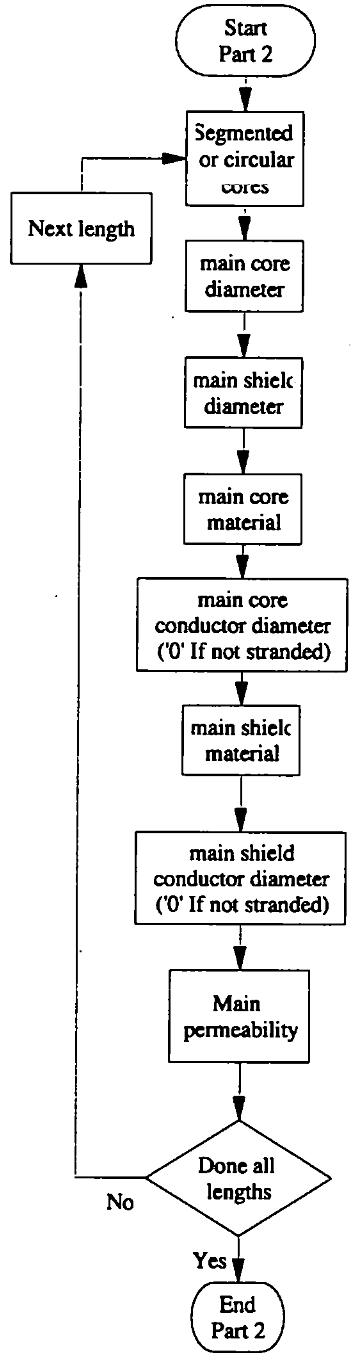

Figure 4.9.b Flow chart for entering network data

4.22 Summary

The programme as described was completed and output was checked with practical results from known networks. These comparisons can be found in chapter 5. The software is completely functional but has limitations because there are no error traps at all to correct an incorrect entry. With several hundred data entries to make for an average network, the chances of entering all data with no errors is minimal so some form of data check and repeat on error needs to be incorporated. The routines needed for this are fairly straightforward and would in this instance only make the programme more difficult to understand. If a version of the software is required for practical use then this would need to be incorporated.

The routines for finding the square root of a three by three matrix should not have been written using roots of polynomials. Because there are four possible roots a decision has to be made as to the correct root. In all the calculations performed so far, of the four possible roots only one has been a sensible answer, with the other three being either negative or of such a magnitude as to be obviously incorrect. This may not always be the case and with hindsight it becomes clear that eigenvector methods for finding the square root should have been used.

A commercial copy of the software must be capable of calculating spur to spur response for any two points on the network. This facility would be needed if a system was defined whereby very low power signals were used with only enough signal strength to reach the next spur on the network at which point the signal would be amplified and/ or frequency shifted for re-transmission. This kind of repeater system could be more useful than blanket transmissions to all connections on the network. The software must also cater for calculation of three phase supplies from the main three phase main cable. These additions are straightforward and were only omitted to facilitate easier understanding of the software.

Chapter 5. Supply Networks

5.1 Introduction

NORWEB's supply network is similar to the type of network used by all the regional electricity supply companies, with the exception of London (see figure 1.2). Within the UK, electricity is supplied to the regional supply companies from the national grid network (275 kV and above) via overhead pylons. At the point of supply will be a substation normally reducing the voltage first to 132 kV then to 33 kV and distributing this supply into between 1 and 10 feeders. These feeders will be between several metres and 5 kilometres in length. Each of these feeders can supply up to five heavy industrial customers or substations, reducing the voltage to 11 kV. Each 11 kV substation will feed between 1 and 10, 11 kV spurs up to 3 kilometres in length, again feeding up to five transformers. Some of the larger customers will be supplied with electricity at this voltage, accepting responsibility for the reduction to normal mains supply themselves, though normally each of the 11 kV spurs will be terminated in another reducing transformer, supplying 240 volt single phase and 415 volt three phase power to customers.

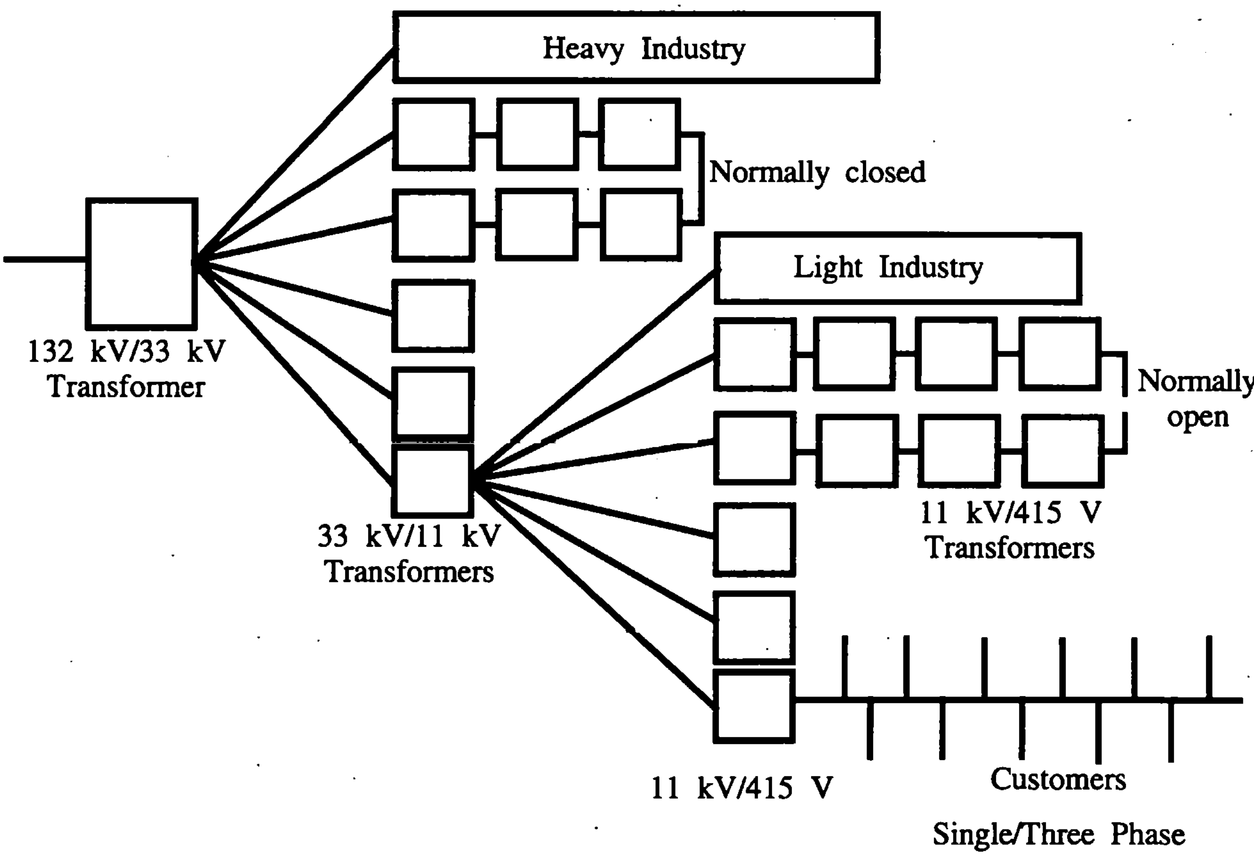

Figure 5.1. Schematic Supply Network

The majority of the transformers used in the supply process are three phase transformers and most supplies at all voltages (11 kV and above) are three phase.

The number of customers supplied from the output of an 11 kV/415 V transformer varies between one for a rural farm supply to around 300 for a large housing estate.

Cable architecture may be overhead or underground, though the majority of supplies are taken from underground cables. The overhead supplies are normally to small remote rural sites.

In normal operation the network topology is that of a tree, with no closed loops. However at all voltages there are normally open points, which when closed will allow a spur to be "back fed" for use in emergencies where a transformer or cable has developed a fault. These points are situated wherever two supplies run physically close together. The provision of this emergency facility does consume power, as the feeder to a normally open point will suffer the effect of capacitive currents (due to cable capacitance) even when the point is open.

5.2 H.V. Sub Stations

The transformer installation at the substation will normally follow the design given in figure 5.2. Wherever possible the inputs to the transformer will originate at different sources. This duplication allows for one of the supplies to develop a fault, which if disconnected will ensure the continued operation of the supply network.

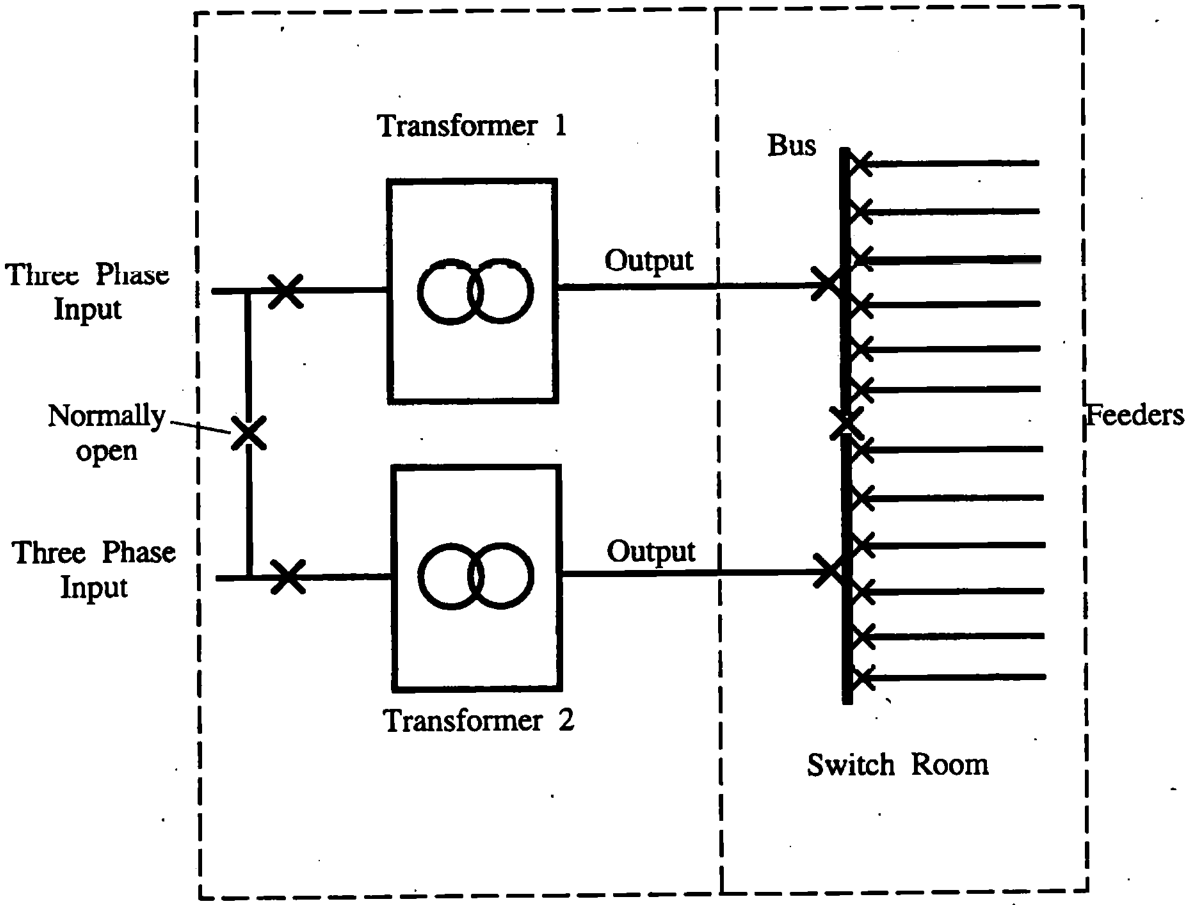

Figure 5.2. Schematic Transformer

5.3 Thirty Three kV Network

The 33 kV network comprises, in the main, single phase conductors running in groups of three, see figure 5.3. If these conductors are overhead they are uninsulated stranded steel core with stranded aluminium outer conductors (aluminium conductor steel reinforced, ACSR). They are uninsulated to assist with heat dissipation. If underground they are single phase, aluminium and stranded copper earth shielded, stranded copper conductor, polythene coated and XLPE (Cross Linked Poly-ethylene) insulated construction. (Modern system)

The 33 kV supply is distributed via a bus bar at the 132 kV/33 kV sub, see figure 5.4.

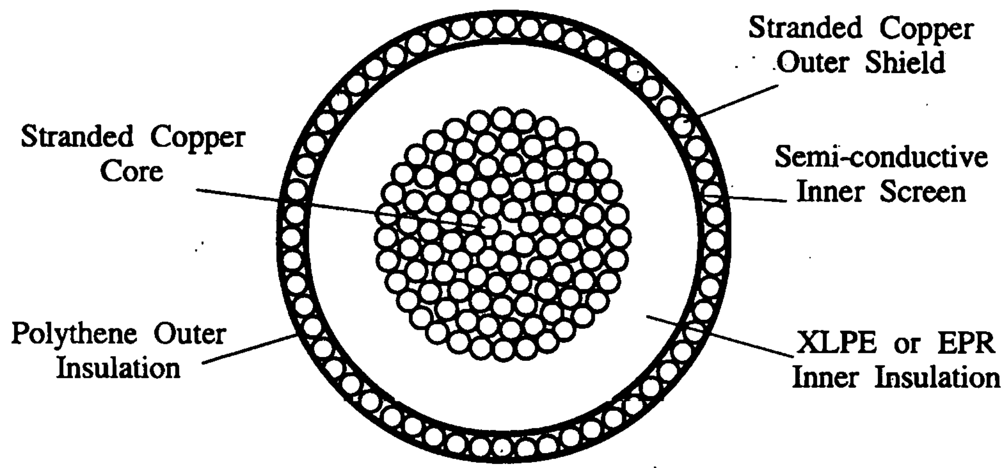

Figure 5.3.
Typical 33 kV Underground Transmission Cable Construction Diagram

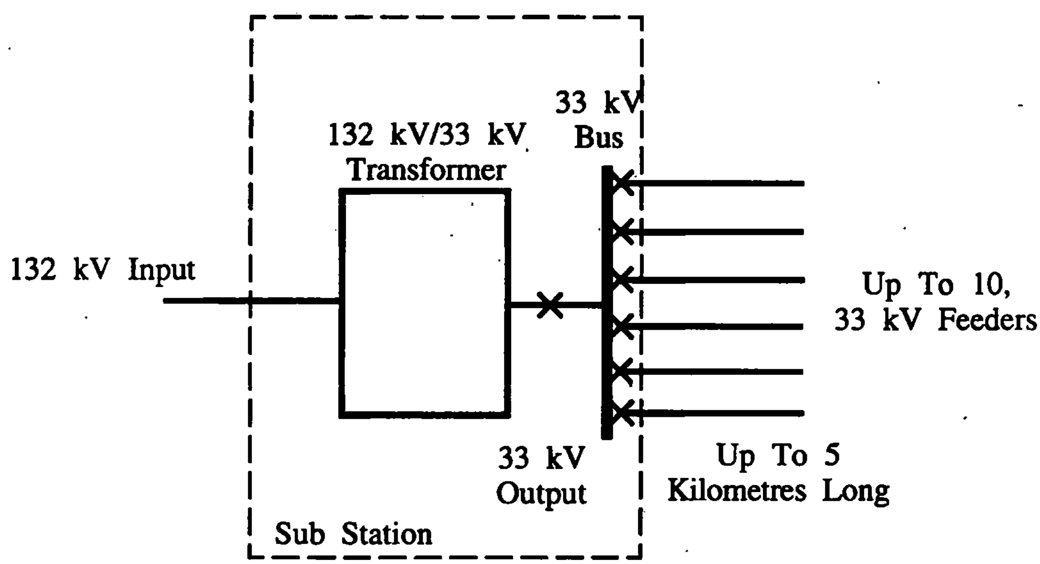

Figure 5.4. 33 kV Transmission Schematic

5.4 11 kV Distribution Network

The 11 kV underground networks comprise three phase single construction cables. The 11 kV overhead networks comprise uninsulated separate solid aluminium conductors flown between overhead supports. A typical underground cable construction is shown in figure 5.5. The 11 kV supply is distributed via a bus bar at the 33 kV/11 kV sub, see figure 5.6.

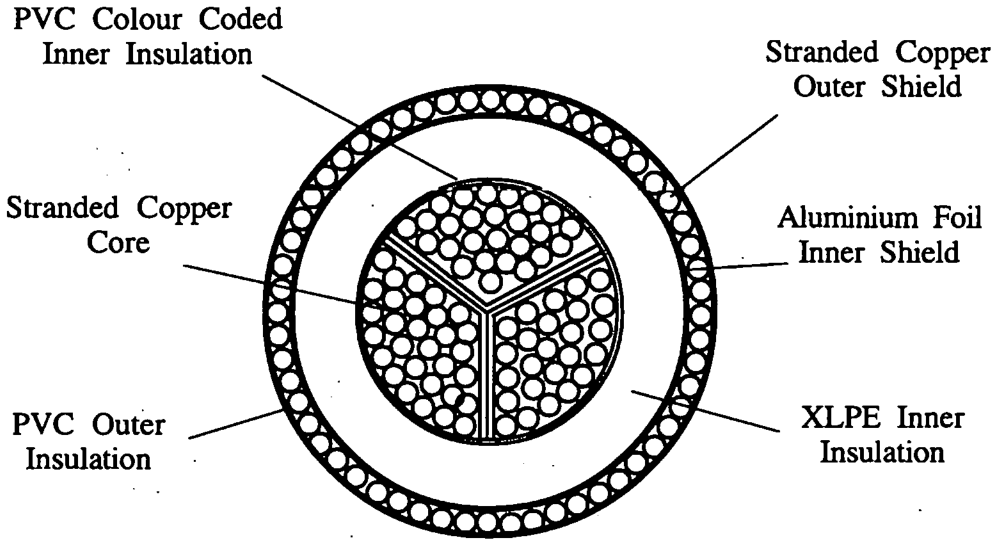

Figure 5.5.
Typical 11 kV Underground Distribution Cable Construction Diagram

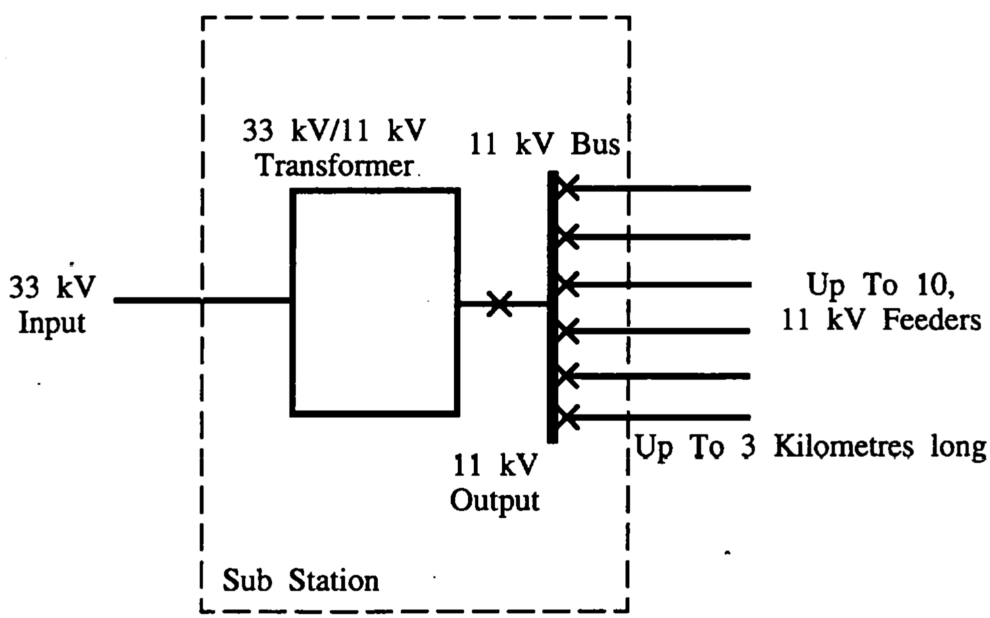

Figure 5.6. Typical 11 kV Primary Schematic

5.5 240 Volt Single Phase / 415 Volt Three Phase Network

The 240/415 volt supply is the UK standard single phase domestic electricity supply. Each LV transformer output can supply multiple spurs feeding up to 300 houses or their equivalent, see figure 5.7. The spurs will normally extend radially from the substation and may extend to 500 metres long. The feed cable is normally three phase and is laid physically close to the premises to be supplied. Outside each customer's premises a joint will be made to the three phase supply, enabling either a three phase or single phase spur to provide the power to the building. In certain circumstances a second supply may be taken from the termination point of the first in order to simplify installation (loop service). This means that occasionally two adjacent houses will be supplied from the same feed. The distances between adjacent supplies and the length of the spur from the house to the main cable is dictated by the geographical layout of the houses and will normally vary from a few metres up to a maximum of 30 metres. The power for street lighting is also taken from the main supply cable. These supplies are single phase and are rated at less than 25 amperes. The choice of phase for any of the supplies is not critical but is designed to give approximately even consumption from each phase in order to minimise neutral/earth currents. The types of cable used for this distribution vary in age, physical characteristics and electrical characteristics.

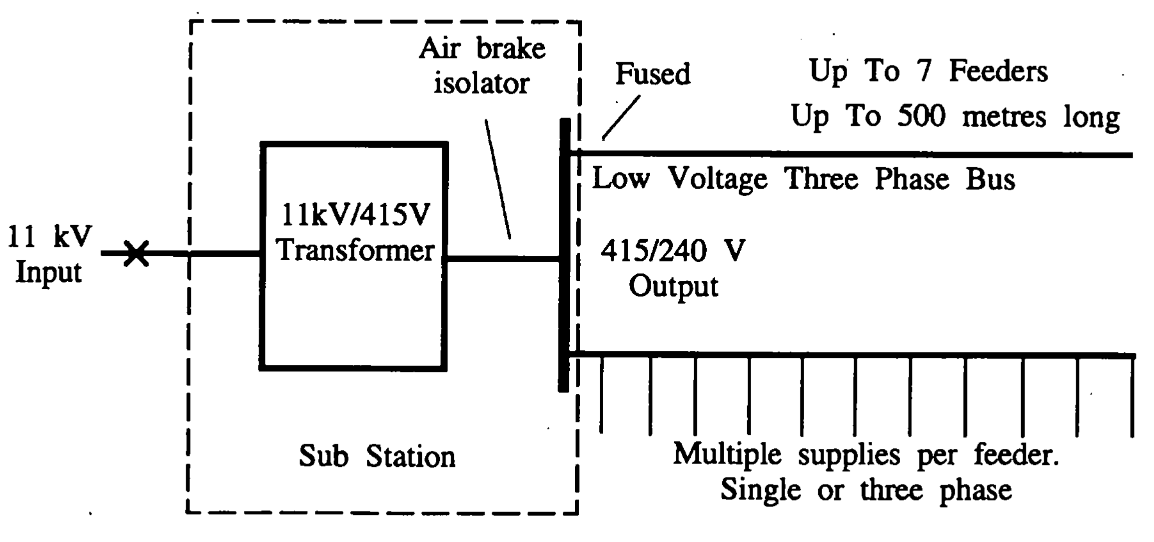

Figure 5.7. 415/240 Volt Distribution Schematic

Modern cables for the low voltage supply are constructed as shown in figure 5.8. The size of cable used depends on the installation– it is normal to reduce cable size as distance from the substation increases. This type of cable is available in four standard sizes, 95 mm^2 , 185 mm^2 , 240 mm^2 and 300 mm^2.

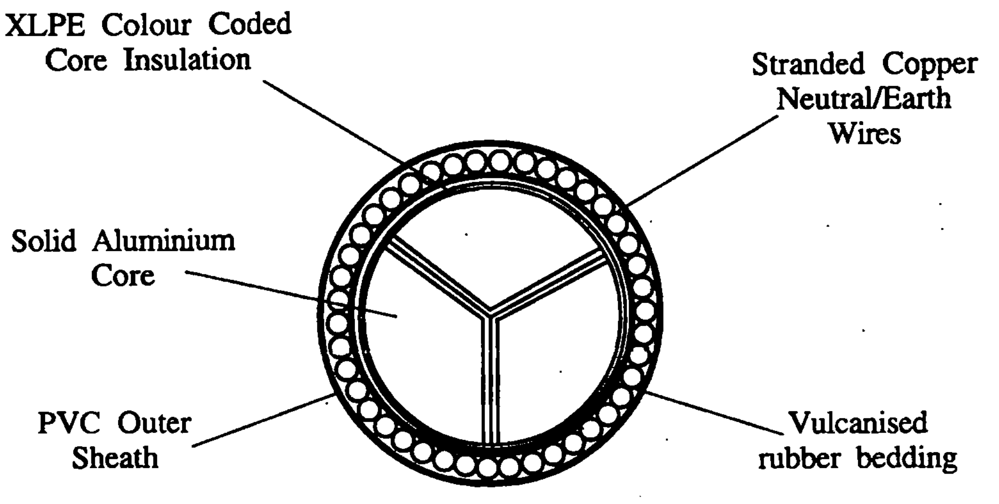

Figure 5.8. 415/240V Modern Underground Waveform

Three Phase Supply Cable, Construction Diagram

The description on the previous page refers to current cabling architecture. As the supplies in the UK can be over 50 years old, there are a lot of different types of cable. On the older types of cable, the conductors will generally be circular (either stranded copper or solid aluminium), the insulation will be oil impregnated paper and the outer shield may be extruded lead or stranded steel, the outer cover was pitch. A common type of supply cable has five cores. The fourth core was used for neutral before protective multiple earth (PME) methods were introduced and the fifth smaller core was used for street lighting. A time related switching device at the substation would control the power to this fifth conductor, allowing the lights to come on when required. This method of street lighting control is now being phased out.

Service cable is used to link the main supply cable spur to the customer premises where the supply is required. The size and specification vary according to the supply required.

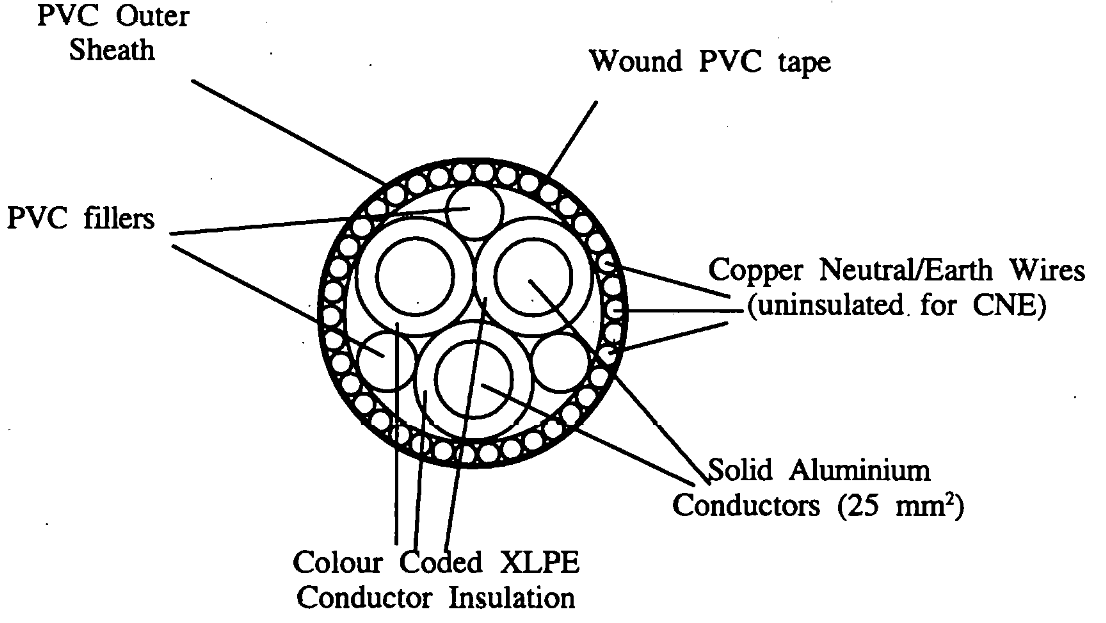

Figure 5.9.

415/240 V Modern Underground Three Phase Service Cable, Construction Diagram

For a normal three phase 100 ampere supply, 25 mm^2 concentric solid aluminium conductor is used (CNE), see figure 5.9. All service cable is available in "split" (SCNE) form. The six elements making up the centre of the cable are tightly bound, distorting the PVC strands and leaving minimal air gaps between the elements.

For a normal single phase domestic 100 ampere supply, 35 mm^2 concentric solid aluminium conductor (CNE) is used, see figure 5.10. This is also available in "split" form.

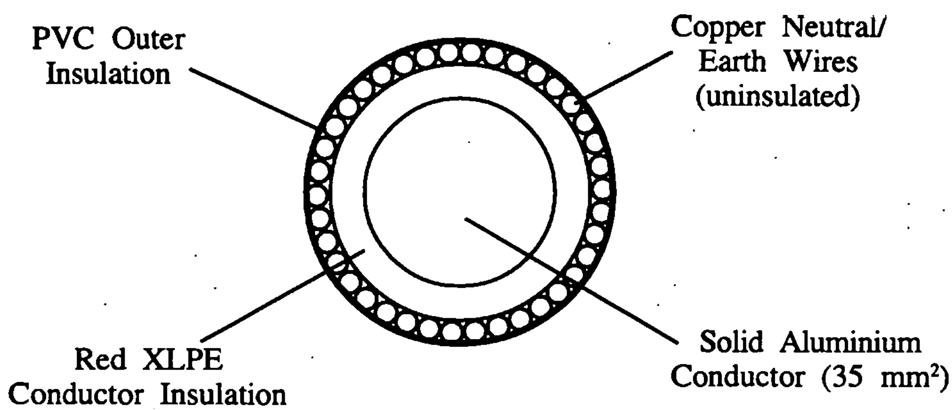

Figure 5.10.

240 V Modern Underground Single Phase Service Cable, Construction Diagram

5.6 Cable Parameters

Several experiments have been performed to determine the transmission line parameters of the low voltage supply cable. These tests were performed on loose pieces of cable in whatever lengths were available, varying from 500 mm for the older types of cable up to full 500 metre drums for the newer types.

	Resistance Ohms	Inductance Henrys	Capacitance Farads
SNR3748	.0012	10^{-6}	400×10^{-12}
95 mm 3ph	.0005	3×10^{-6}	300×10^{-12}
Old 3ph (CU)	.00008	1.5×10^{-6}	173×10^{-12}
95 mm Paper	.0015	$.5\times10^{-6}$	280×10^{-12}
25mm 3ph	.002	1.3×10^{-6}	400×10^{-12}

Table 5.1. Measured cable parameters

Table 5.1 shows a sample of the measured electrical characteristics for the types of cable used for distribution.

These figures are experimental results corrected for a one metre length. They were measured using meters and pulse reflection equipment with the average values being taken. The value for resistance is a DC value, the values for inductance and capacitance varied depending on the method used for measurement. None of the equipment available was capable of returning any value for the admittance of the cable. The measurements were taken on the longest length we had available. The newer cable was available in lengths up to 500 metres, on drums, but the older cable was only available in short lengths where the cable had been removed from site due to faults or during normal maintenance work.

Cable parameters can be calculated from the physical dimensions of the cable. The following is a typical example for a 33 kV single phase cable with a copper stranded core, XLPE insulation and a copper stranded shield as shown in figure 5.11

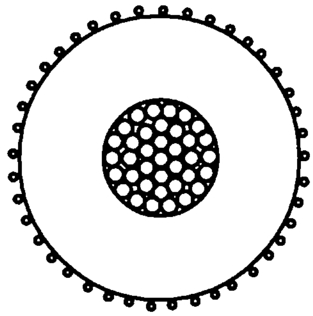

Figure 5.11. 33 kV XLPE Underground Single Phase Cable (c. 1994).

Cable Dimensions

3 mm outer insulation thickness. 37.5 mm inner insulation diameter, 11 mm thick (XLPE).

Screen Copper

41 Uninsulated conductors 1.25 mm conductor diameter.

Centre cores Copper

37 Uninsulated conductors 2.5 mm, total diameter 15.5 mm.

Cross sectional area.

41 × 1.25 mm diameter gives 50×10^{-6} m^2

37 × 2.5 mm diameter gives 185×10^{-6} m^2

This gives a total X-sect. area for the screen of 50×10^{-6} m^2

and a total X-sect. area for the core of 185×10^{-6} m^2.

Below is an example of cable parameters at 1 MHz.

From equation 44, conductance 'G' per metre

$$G = \frac{2 \times \pi \times \sigma}{\ln \frac{b}{a}} = \frac{2 \times 3.14 \times 10^{-16}}{\ln \frac{37.5}{15.5}} = 7.11 \times 10^{-16} \text{siemens per metre,}$$

and capacitance 'C' per metre

$$C = \frac{2 \times \pi \times \varepsilon}{\ln \frac{b}{a}} = \frac{2 \times 3.14 \times 3.5 \times 8.855 \times 10^{-12}}{\ln \frac{37.5}{15.5}} = 220.1 \times 10^{-12} \text{ farads per metre,}$$

Inductance 'L' per metre using equation 65

$$L = \frac{\mu_0 \varepsilon}{C} = \frac{4\pi \times 10^{-7} \times 3.5 \times 8.855 \times 10^{-12}}{220.1 \times 10^{-12}} = 176 \times 10^{-9} \text{ henrys per metre.}$$

Resistance 'R' per metre

DC resistance $,R = \frac{\rho}{A}$ (102)

Using equation 61, skin depth (δ) for copper conductors

$$\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}} \qquad \rho = 1.673 \times 10^{-8}, \mu = 4 \times \pi \times 10^{-7}$$

$$\delta = \sqrt{\frac{1.673 \times 10^{-8}}{\pi^2 \times 4 \times 10^{-7} \times f}} = \frac{0.065}{\sqrt{f}}$$

At 1MHz the effective cross sectional area of each shield conductor is:-

$$\text{Area} = \pi \times (0.625 \times 10^{-3})^2 - \pi \times \left[0.625 \times 10^{-3} - \frac{0.065}{\sqrt{10^6}}\right]^2 = 2.42 \times 10^{-7} \text{ m}^2$$

Total screen area = $41\times2.42\times10^{-7}=9.9\times10^{-6}$ m^2

Using equation 102 the resistance of one metre of the screen is therefore

$$R_1=\frac{\rho}{A}=\frac{1.673\times10^{-8}}{9.9\times10^{-6}}=1.69\times10^{-3}\ \Omega$$

The core is made up of 37 tightly bound stranded copper conductors of radius 2.5 mm, calculations for skin depth will treat the core as a solid copper bar of diameter 15.5 mm.

$$\text{Area}=\pi\times(7.75\times10^{-3})^2-\pi\times\left[7.75\times10^{-3}-\frac{0.065}{\sqrt{10^6}}\right]^2=3.15\times10^{-6}\ \text{m}^2$$

This figure represents a hollow cylinder of outside diameter 15.5 mm and inside diameter of 15.5-3.15×10^{-6}mm. If the conductor is as in this case, stranded, then the non-circular circumference of the core will further reduce the effective area and this must be accounted for.

From equation 102 the resistance of the core cylinder will be:-

$$\frac{\rho}{A}=\frac{1.673\times10^{-8}}{3.15\times10^{-6}}=5.30\times10^{-3}\Omega$$

Modifying this with the ratio from equation 64 gives :-

$$R_2=\frac{\rho}{A}\times\frac{2\times\text{Rad}\times\delta}{\text{A}\cos\left[\frac{(\text{Rad}-\delta)}{\text{Rad}}\right]\times\text{Rad}^2-(\text{Rad}-\delta)\sqrt{\text{Rad}^2-(\text{Rad}-\alpha)^2}}$$

$$R_2=5.3\times10^{-3}\times4.67=24.8\times10^{-3}\Omega$$

This gives a total resistance per metre at 1 MHz of R_1+R_2

$$R=R_1+R_2=1.69\times10^{-3}+24.8\times10^{-3}=26.4\times10^{-3}\Omega$$

The inductance of the cable will not be modified by a significant amount as frequency varies. Provided the permittivity and resistivity of the insulators do not vary with frequency, the capacitance and conductance of the cable will also remain unchanged. The value of ε will vary with frequency but this variation is small and has been ignored. [Ref. 17]

Using the methods outlined in chapter 4 the theoretical response of the cable was calculated and the practical response was obtained from tests, using the circuit in figure 5.12.

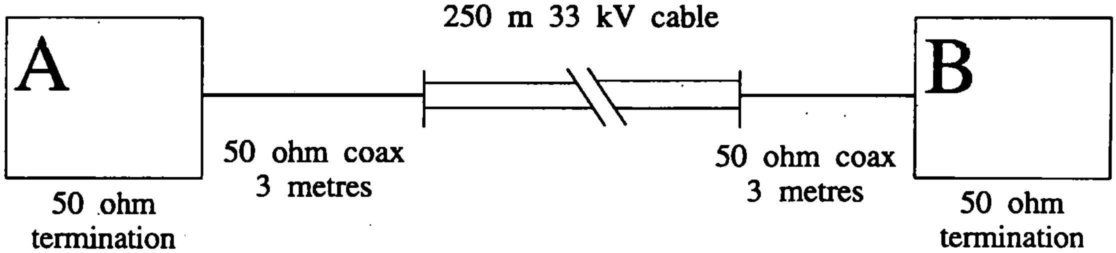

Figure 5.12. Test set up for 33 kV cable

Equipment used for test

A) Marconi 2955 transmitter/receiver test set. Output into 50 ohms set to 0 dBm

B) Marconi spectrum analyser, 50 ohms termination impedance.

The Marconi 2955 test set is designed for use with 50 ohm systems. The output displayed is the power that would be injected if the device being driven were 50 ohms. In this case the impedance of the cable is unknown, so a figure of 0 dBm on the 2955 will not be true unless the cable is 50 ohms. However from the practical test results in figure 5.13 the fluctuation in output power with frequency is small, suggesting that the system is not badly mismatched and the value for Z_0 calculated from theoretical results puts the VSWR at approximately 0.6. If the 2955 source voltage is constant, these figures put the percentage error at approximately 5%.

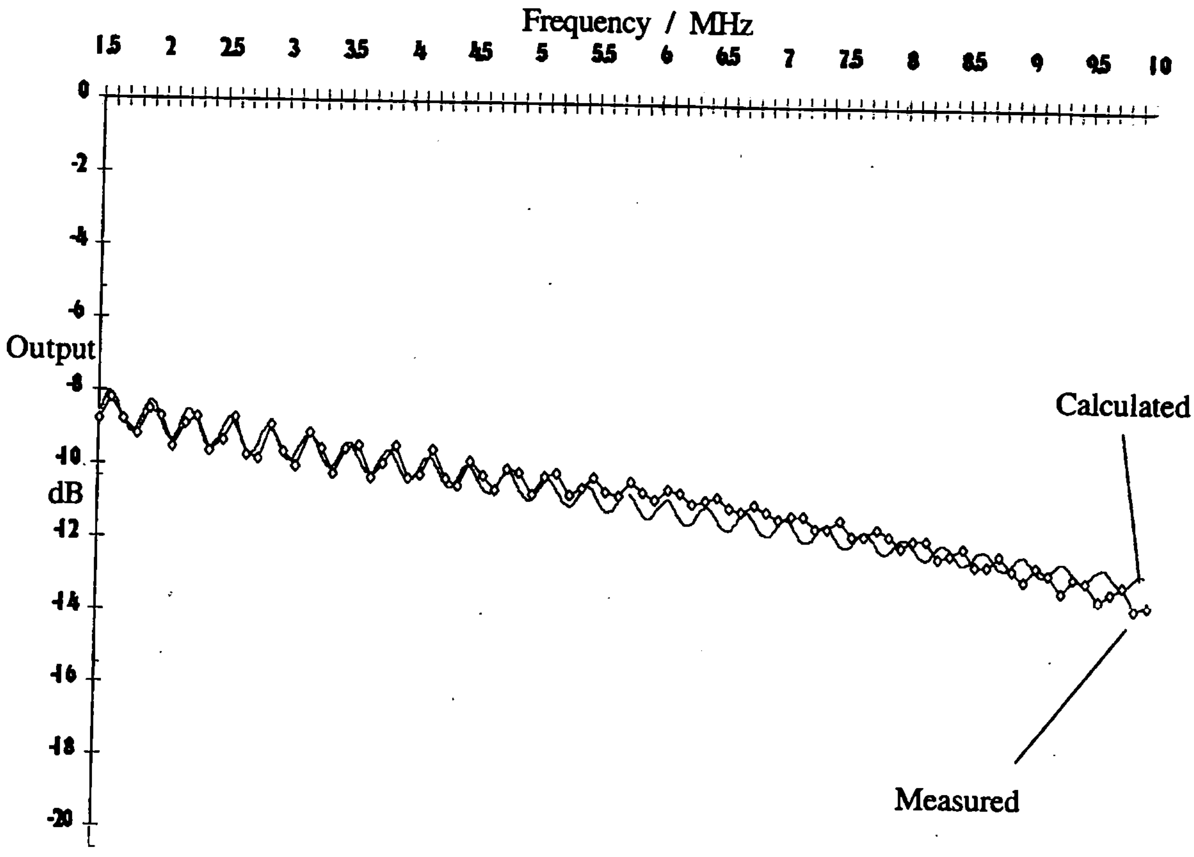

Figure 5.13. Theoretical and practical response of 33 kV cable.

The practical and theoretical results match quite well. The practical result has been modified by subtracting 6 dB in order to show output voltage with respect to source voltage, in dB, instead of output voltage with respect to source output voltage by moving the source reference to the source voltage side of the source resistor.

5.7 11 kV Cable

This cable is the type now being installed for 11 kV supply, see figure 5.14. The shield of the cable is corrugated to allow for easy bending. Because of the variable distance from shield to central conductors, affecting capacitance and the increase in length of the shield, affecting resistance, calculation of the cable parameters is more difficult.

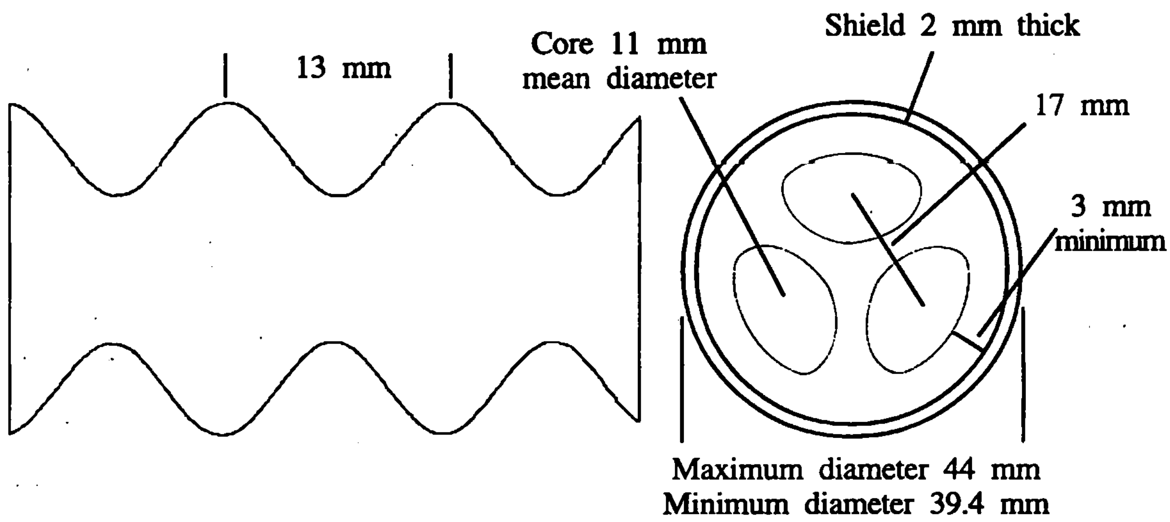

Figure 5.14. 95 mm², 11 kV waveform cable construction diagram (c 1994).

Cable Dimensions

Screen Aluminium

2 mm thick, maximum outside diameter 44 mm,
minimum outside diameter 39.4 mm

Centre cores Aluminium

The core conductors are not circular or sector shaped in cross-section. For the purposes of calculation they will be treated as circular.

36 uninsulated conductors 1.83 mm diameter

Insulation oil impregnated paper

On three phase cable, signals can be injected using several different methods, see figures 5.15 to 5.19. During these tests all terminations were 50 Ω.

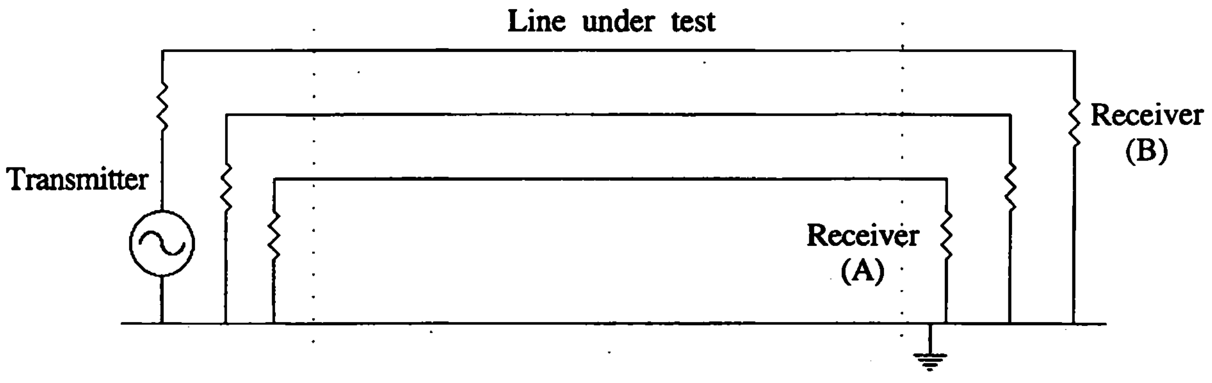

Figure 5.15. Injection and recovery (phase to ground) from same phase (A) and different phases (B) with unused phases terminated

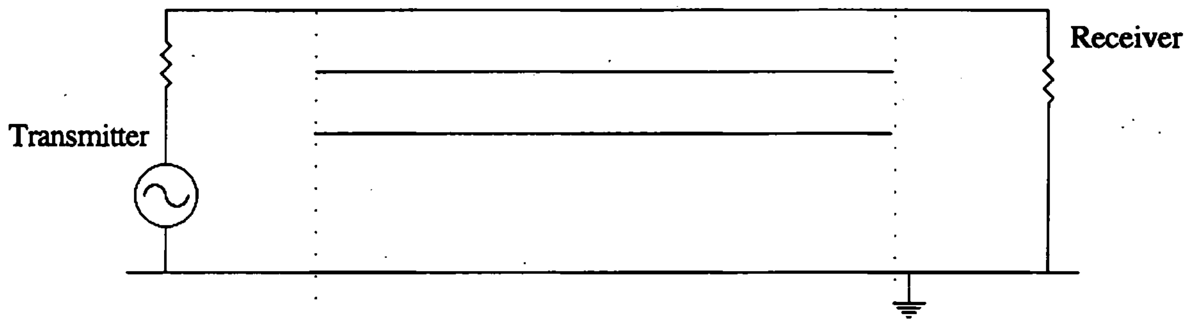

Figure 5.16.
Injection and recovery (phase to ground) from same phase with unused phases not terminated

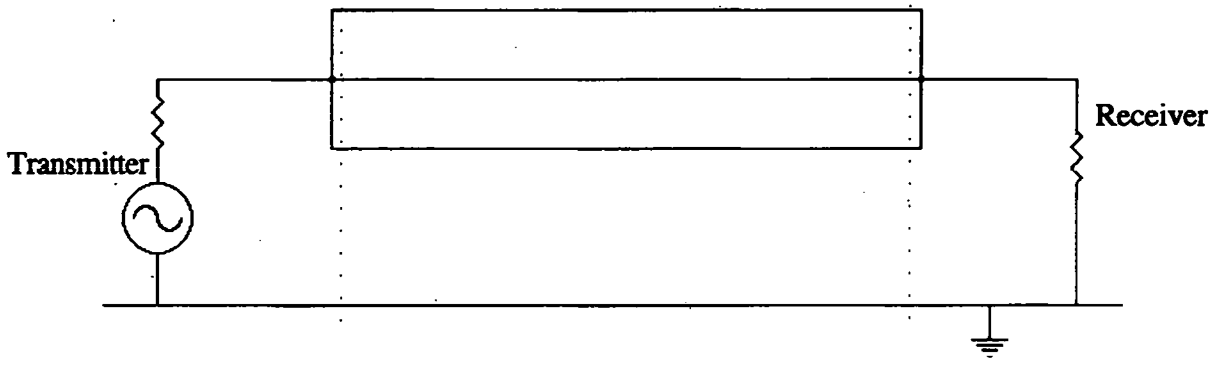

Figure 5.17. Injection and recovery (phase to ground) from all phases.

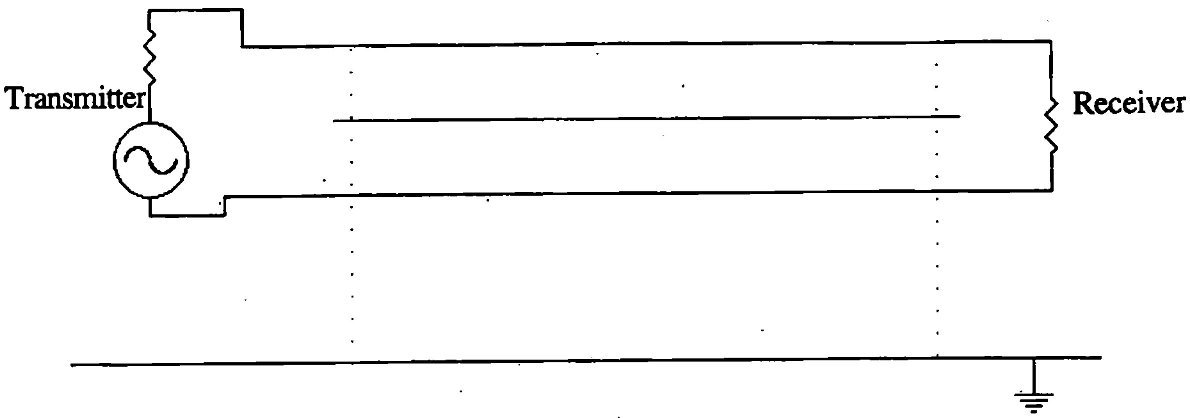

Figure 5.18. Injection and recovery (phase to phase).

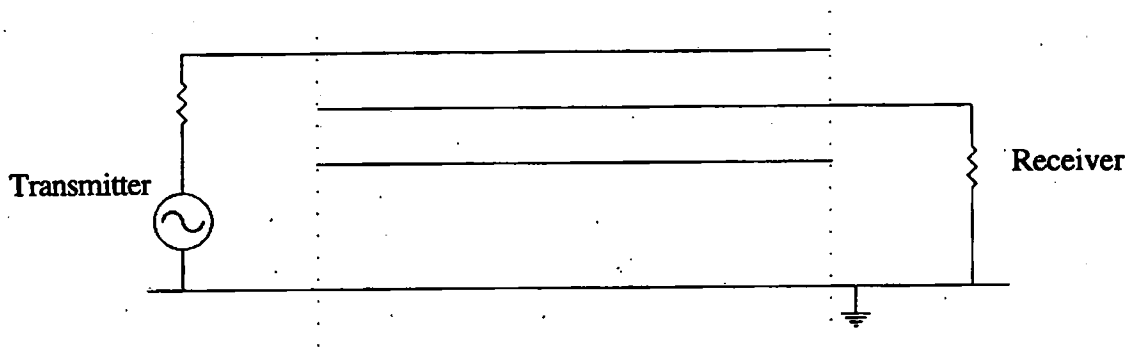

Figure 5.19.
Injection and recovery (phase to ground) from different phases with unused phases not terminated

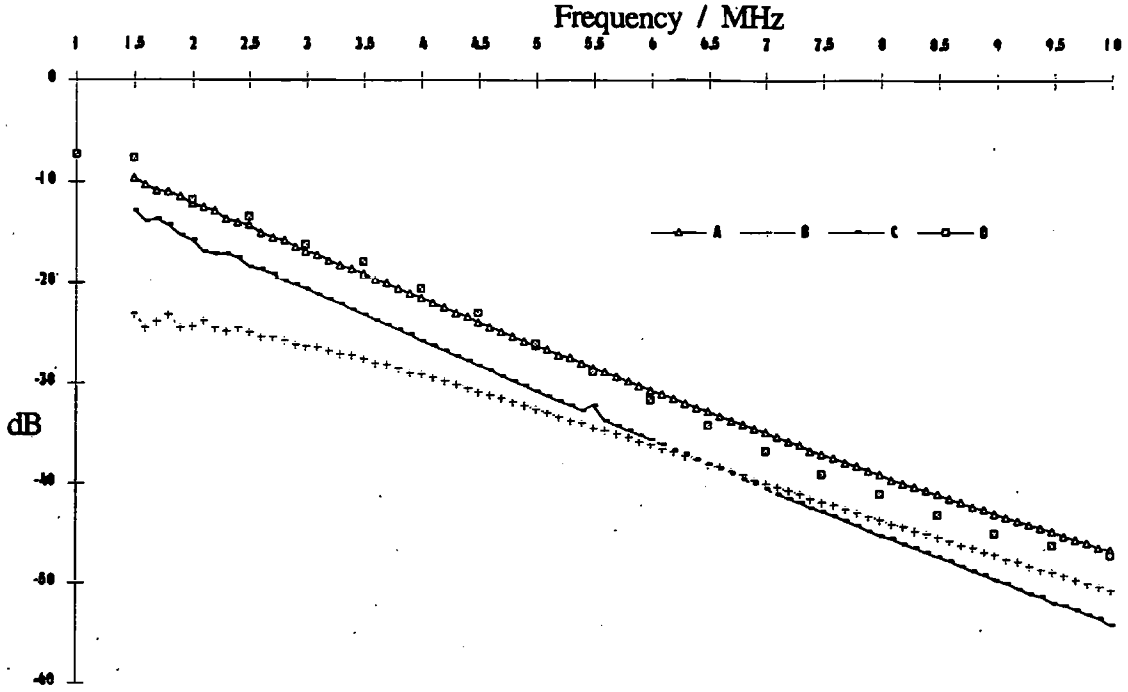

Figure 5.20.
Practical response of 250 metres of 11 kV cable
with different methods of injection/recovery

Key to figure 5.20

A) As figure 5.15 B

B) As figure 5.15 A

C) As figure 5.17

D) As figure 5.16

Figure 5.20 shows the varying different responses from the different injection/ recovery methods shown in figures 5.15 through 5.19. This shows that the cross talk on this type of cable is very high. The difference between injection/recovery from the same phase and cross injection/recovery from different phases is small as is the difference between single phase injection/recovery and multiple phase injection/ recovery

Each of the three cores is made up of 36 strands of tightly bound aluminium. The shield is solid aluminium. In a one metre length of cable the shield will be significantly longer than one metre as shown.

From equation 60, length of a curve $= \int_a^b \sqrt{(1+\left[\frac{dy}{dx}\right]^2)}dx$

Length of positive half cycle of a sine wave of amplitude 1.5 mm period 13 mm 'L1'.

$$L1 = \int_0^{6.5} \sqrt{1+\left[\frac{1.5\times\pi}{6.5}\right]\times\cos^2\left[\frac{x\times\pi}{6.5}\right]}dx = 7.284\,\text{mm}$$

Total length of screen in one metre of cable is 154 × 7.284 = 1121.7 mm. This is an increase of 12%.

Following is an example of cable parameters at 1 MHz.

Capacitance between cores 'C_c' per metre from equation 52.

$$C_c = \left[20.03\times\left[\frac{5.5}{17}\right]^2 - 4.54\times\frac{5.5}{17} + 1.50\right]\times 8.855\times10^{-12}\times3 = 56.5\times10^{-12} \text{ farads per metre.}$$

Capacitance between core and shield 'C_s' per metre

The value of capacitance will not significantly affect the attenuation of the cable but will affect the standing waves, reflections and phase shifts within the cable. If the cable is not terminated with Z_0, variation in capacitance changes the frequency range between maxima and minima on the attenuation with frequency cable response.

From equation 56:

$$C_s = \left[149.8 \times \left[\frac{55}{17}\right]^2 - 37.44 \times \frac{55}{17} + 5.44\right] \times 8.855 \times 10^{-12} \times 3 - 56.5 \times 10^{-12} = 183 \times 10^{-12} \text{ farads per metre.}$$

From equation 65. Inductance 'L' per metre (core to shield)

$$L_s = \frac{\mu_0 \varepsilon}{C_s} = \frac{4\pi \times 10^{-7} \times 3 \times 8.855 \times 10^{-12}}{\times 135 \times 10^{-12}} = 247 \times 10^{-9} \text{ henrys per metre.}$$

From equation 66. Inductance 'L' per metre (core to core)

$$L_c = \frac{\mu_0 \varepsilon}{2C_c} = \frac{4\pi \times 10^{-7} \times 3 \times 8.855 \times 10^{-12}}{2 \times 107 \times 10^{-12}} = 155 \times 10^{-9} \text{ henrys per metre.}$$

Conductance 'G' per metre (core to core) from equation 52

$$G_c = \left[20.03\times\left[\frac{5.5}{17}\right]^2 - 4.54\times\frac{5.5}{17} + 1.50\right]\times 10^{-16} = 2.13\times 10^{-16} \text{ siemens per metre.}$$

Conductance 'G' per metre (core to shield) from equation 56

$$G_s = \left[149.8\times\left[\frac{5.5}{17}\right]^2 - 37.44\times\frac{5.5}{17} + 5.44\right]\times 10^{-16} - 2.13\times 10^{-16} = 6.88\times 10^{-16} \text{ siemens per metre.}$$

Shield resistance per metre 'Rss'

Skin depth (δ) for aluminium conductors (equation 61)

$$\delta = \sqrt{\frac{\rho}{\pi\times f\times\mu}} \qquad \rho = 2.655\times 10^{-8},\ \mu = 4\times\pi\times 10^{-7}$$

$$\delta = \sqrt{\frac{2.655\times 10^{-8}}{\pi^2\times 4\times 10^{-7}\times f}} = \frac{0.082}{\sqrt{f}}$$

Shield effective cross sectional area

$$A_{ss} = \pi\times\left[19.7\times 10^{-3} + \frac{0.082}{\sqrt{10^6}}\right]^2 - \pi\times(19.7\times 10^{-3})^2 = 10.2\times 10^{-6}\,\text{m}^2$$

$$R_{ss} = \frac{\rho}{A_s}\times 112\% = \frac{2.655\times 10^{-8}}{10.2\times 10^{-6}}\times\frac{112}{100} = 2.9\times 10^{-3}\ \Omega \text{ per metre,}$$

Core resistance per metre 'Rcs'

Effective core area 'Acs'

$$A_{cs} = \pi\times(5.5\times10^{-3})^2 - \pi\times\left[5.5\times10^{-3} - \frac{0.082}{\sqrt{10^6}}\right]^2 = 2.80\times10^{-6}\mathrm{m}^2$$

Modifying this with the ratio from equation 64 gives :-

$$R_{cs} = \frac{\rho}{A_{cs}}\times\frac{2\times \mathrm{Rad}\times\delta}{\mathrm{A\cos}\left[\frac{(\mathrm{Rad}-\delta)}{\mathrm{Rad}}\right]\times \mathrm{Rad}^2 - (\mathrm{Rad}-\delta)\sqrt{\mathrm{Rad}^2-(\mathrm{Rad}-\alpha)^2}}$$

$$R_{cs} = \frac{\rho}{A_{cs}\times \mathrm{ratio}} = \frac{2.655\times10^{-8}}{2.8\times10^{-6}}\times3.592 = 34.1\times10^{-3}\ \Omega \text{ per metre.}$$

Total resistance for one metre 'Rs'

$$R_s = R_{ss} + R_{cs} = 2.9\times10^{-3} + 34.1\times10^{-3} = 37.0\times10^{-3}\Omega \text{ per metre.}$$

This is the most complicated cable used by NORWEB and the calculation of the parameters for this type of cable involves more approximations than any other type. The calculated response of this cable using the parameters given does not follow the practical response because of the approximations made in these calculations. The calculated response does however provide a reasonable approximation of the practical response. Allowing for these approximations it suggests that the equations used are valid and that the functions written for applying the equations are working correctly. Unfortunately this type of cable was the only type of three phase cable available in reasonable lengths for practical tests, see figures 5.21 and 5.22.

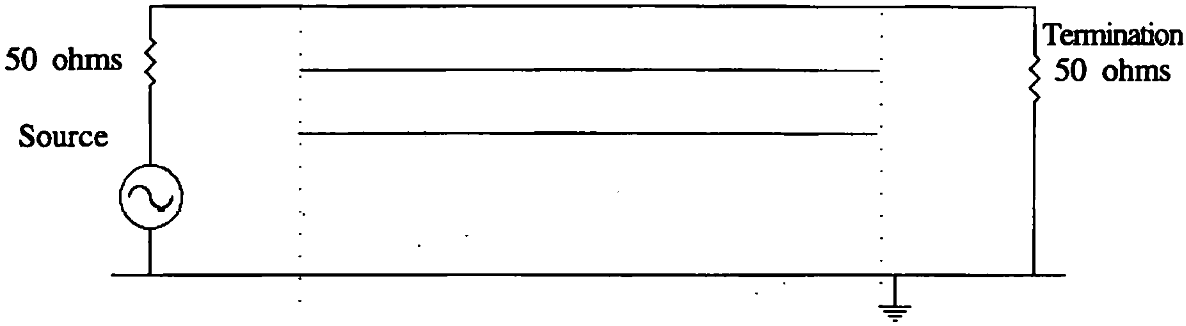

Figure 5.21.
Circuit used for calculation of cable response

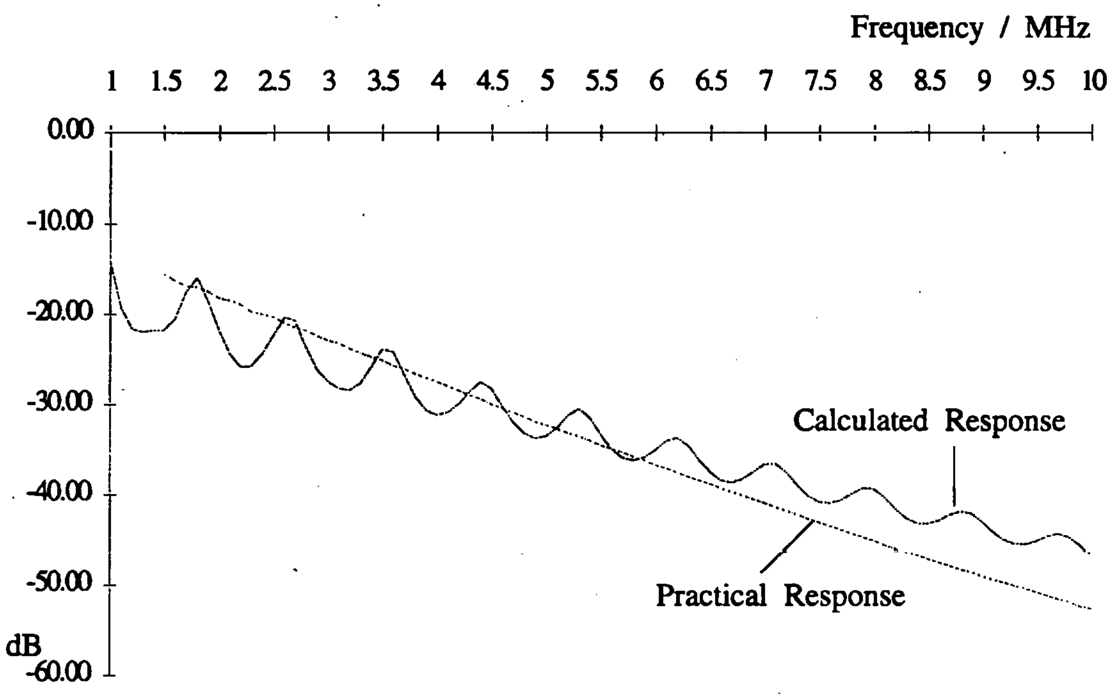

Figure 5.22.
Practical response versus calculated response of 250 metres of 11 kV cable

5.8 240/415 volt. Low Voltage Supply Cable

25 mm XLPE cable is the type currently fitted for supplying a three phase 100 amp supply, to customers, from the main low voltage feeder. The construction of this cable is shown infigure 5.23 and the simplified diagram used for calculation of transmission line parameters is shown in figure 5.24.

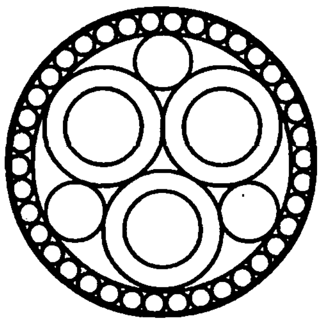

Figure 5.23. 25mm XLPE cable

2.6 mm Outer Insulation

<u>Screen</u> Copper

24 Insulated conductors	1.6 mm with insulation	0.9 mm conductor
8 Uninsulated conductors	1.6 mm conductor	
2 Insulators	2.0 mm diameter	

<u>Centre cores</u> Aluminium

3 insulated conductors	8 mm with insulation	5.64 mm conductor

<u>Cross sectional area.</u>

8×1.6 mm diameter gives 2.01×10^{-6} m^2

24×0.9 mm diameter gives $.636 \times 10^{-6}$ m^2

This gives a total X-sect area for the screen of 31.35×10^{-6} m^2 and a total X-sect area for the cores of 5.64 mm diameter giving 25×10^{-6} m^2 per core.

Assume outer screen is a solid tube of inside radius 8.62 mm

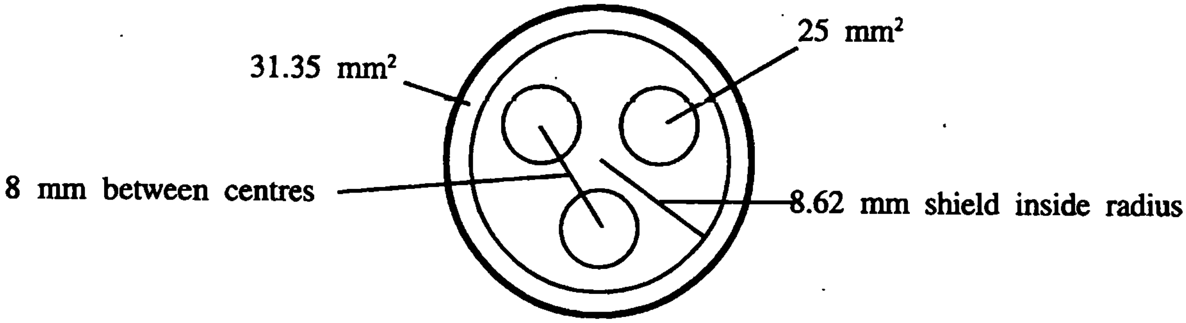

Figure 5.24.

Equivalent construction of 25 mm XLPE Split cable for calculation purposes.

Conductance core to core 'G_1' per metre of

$$G_1 = \left[20.03 \times \left[\frac{2.8}{8.6}\right]^2 - 4.54 \times \frac{2.8}{8.6} + 1.50\right] \times 10^{-16} = 2.15 \times 10^{-16} \text{ siemens per metre}$$

and a conductance between conductor and shield 'G_2' per metre of :

$$G_2 = \left[149.8 \times \left[\frac{2.8}{8.6}\right]^2 - 37.44 \times \frac{2.8}{8.6} + 5.44\right] \times 10^{-16} - 2.15 \times 10^{-16} = 6.98 \times 10^{-16} \text{ siemens per metre}$$

With PVC and XLPE cable this value is very stable both with temperature and age and is too small to affect any calculations.

Capacitance between cores.

$$C_C = \left[20.03\times\left[\frac{2.8}{8.6}\right]^2 - 4.54\times\frac{2.8}{8.6} + 1.50\right]\times 8.855\times 10^{-12}\times 3 = 57.0\times 10^{-12} \text{ farads per metre}$$

Capacitance between parallel cylinders.

R=2.82mm, D=8mm.

$$C_s = \left[149.8\times\left[\frac{2.8}{8.6}\right]^2 - 37.44\times\frac{2.8}{8.6} + 5.44\right]\times 8.855\times 10^{-12}\times 3 - 57.0\times 10^{-12} = 185\times 10^{-12} \text{ farads per metre}$$

Inductance of a cylindrical conductor due to external flux linkages, equation 65.

$$L = \frac{\mu_0}{2\pi}\ln\left[\frac{D-R}{R}\right] = 2\times 10^{-7}\times\ln\left[\frac{8-2.82}{2.82}\right] = 0.122\times 10^{-6} \quad \text{henrys per metre}$$

R=2.82 mm, D=8 mm.

Where R is the core radius and D is the distance between conductors.

Skin depth (δ) for copper conductors (equation 61).

$$\delta=\sqrt{\frac{\rho}{\pi\times f\times\mu}} \qquad \rho=1.673\times10^{-8},\mu=4\times\pi\times10^{-7}$$

$$\delta=\sqrt{\frac{1.673\times10^{-8}}{\pi^2\times4\times10^{-7}\times f}}=\frac{0.065}{\sqrt{f}}$$

At 1 MHz the effective cross sectional area of each uninsulated conductor is:-

$$\text{Area}=\pi\times0.0008^2-\pi\times\left[0.0008-\frac{0.065}{\sqrt{10^6}}\right]^2=.313\times10^{-7}\ \text{m}^2$$

Area of 8 off is 2.51×10^{-7} m^2

At 1 MHz the effective cross sectional area of each insulated conductor is:-

$$\text{Area}=\pi\times0.00045^2-\pi\times\left[0.00045-\frac{0.065}{\sqrt{10^6}}\right]^2=.171\times10^{-6}\ \text{m}^2$$

Area of 24 off is 4.10×10^{-6} m^2

Cross sectional area of shield is :-

$4.10\times10^{-6}+2.51\times10^{-6}=6.60\times10^{-6}$ m^2

Resistance of shield per metre (r_s) is :-

$$r_s=\frac{\sigma}{A}=\frac{1.673\times10^{-8}}{6.60\times10^{-6}}=2.53\times10^{-3}\ \Omega$$

Core resistance per metre (r_c) is :-

Skin depth (δ) for aluminium conductors (equation 61).

$$\delta=\sqrt{\frac{\rho}{\pi\times f\times\mu}} \qquad \rho=2.655\times10^{-8},\mu=4\times\pi\times10^{-7}$$

$$\delta=\sqrt{\frac{2.655\times10^{-8}}{\pi^2\times4\times10^{-7}\times f}}=\frac{0.082}{\sqrt{f}}$$

At 1 MHz the effective cross sectional area of each core conductor is:-

$$\text{Area}=\pi\times0.00564^2-\pi\times\left[0.00564-\frac{0.082}{\sqrt{10^6}}\right]^2=2.88\times10^{-6}\ \text{m}^2$$

Resistance of core per metre (r_c) is :-

$$r_c=\frac{\sigma}{A}=\frac{2.655\times10^{-8}}{2.88\times10^{-6}}=9.20\times10^{-3}\ \Omega$$

giving a total resistance per metre (r) in ohms at 1 MHz of r_c+r_s

$$r=9.2\times10^{-3}+2.53\times10^{-3}=11.73\times10^{-3}\ \Omega$$

Using the same method the core resistance per metre at 10 MHz becomes r_c = 28.96×10^{-3} Ω

and the shield resistance at 10 MHz becomes

r_s = 7.82×10^{-3} Ω

giving a total resistance of, $r = r_c+r_s = 36.8\times10^{-3}\ \Omega$

There are certain assumptions made in these calculations.

They are:-

1) That each of the strands in a stranded conductor carries the same current. In practice this is not the case. If the signal carrying core is not concentric with the shield, the shield conductors closest to the core will be subject to greater magnetic fields than the shield conductors further away. This causes greater mutual inductance between core and closest shield conductors. This effect increases with frequency. At DC the resistance of the shield conductors is the only opposition to current flow and thc current will therefore divide equally between them. As the frequency increases the mutual inductance causes the shield current to travel down the path of lowest impedance, namely the conductors furthest from the signal carrying core [Ref. 15]. This effect is not apparent at power frequencies. Because of the helical construction of the shield conductors, current will migrate between them if the shield conductors are touching each other.

2) That the length of the shield conductors is not increased by the helical construction of the shield. This is not the case, the helical construction will add approximately 2% to the length of the conductors. [Ref. 16]

3) That no current flows below the skin depth. This is not the case but the assumption is often made in calculations of this type [Ref. 14].

Chapter 6. Practical Testing and results.

6.1 Introduction

Most of this research has been aimed towards providing a communication channel between the customer and the low voltage substation situated at the origin of that customers electricity supply. This provides the "last drop" of what could be a national communications network. Equipment for the 33/11 kV and higher voltages in the supply chain is difficult to design because of the high working voltage needed for components and difficult to organise because of the need for supervision by qualified and authorised personnel. However, the work continues and units are being designed for interfacing to HV supply networks. The practical results in this chapter refer mainly to the electricity distribution and communication distribution over the LV distribution networks, this being the area of concentration during the research project.

6.2 Customer terminations.

Immediately at the end of the service cable within the customer's premises is the customer's cutout (HRC fuse) followed by the meter and the customer's consumer unit, see figure 6.1. The fuse will normally be rated at 100 amperes and conforms to BS1361, there are three of these fuses for a three phase supply. Up to and including the meter is the property of the electricity company and it is after this point that the customer's own wiring takes over. From a normal domestic supply a customer is permitted to take up to 100 amperes. This represents a termination impedance of magnitude 2.5 ohms, though it will never, in practice, be so low. If a customer is not using electricity then the impedance magnitude is infinity. A communication system with a load impedance of such variable magnitude cannot be very efficient in its use of power. For this reason a termination device was designed by NORWEB in order that communication signals would be presented with a known fixed termination, while the transmission of power at lower frequencies was not impeded in any way, see figures 6.2 through 6.4.

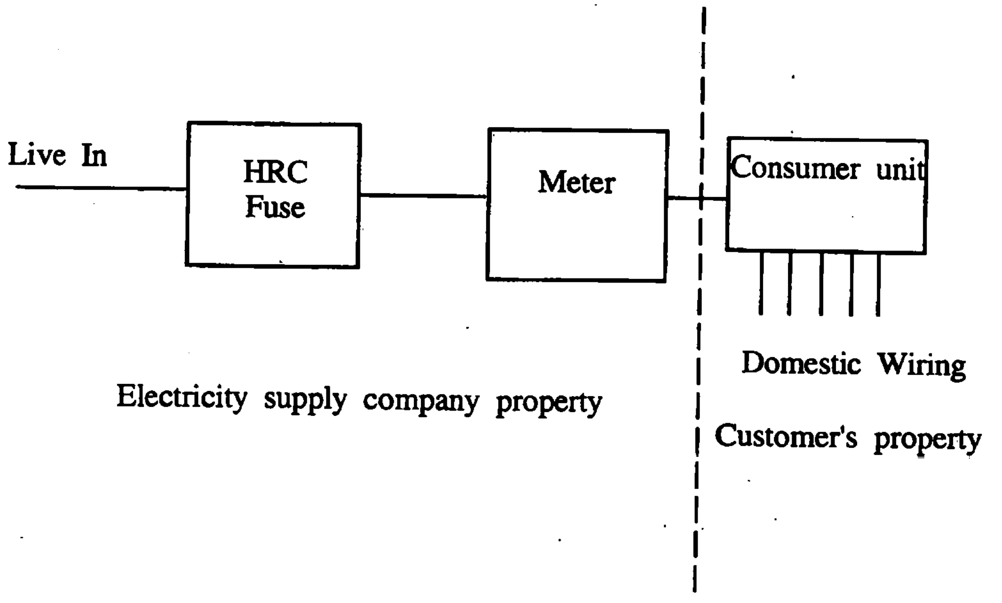

Figure 6.1. Normal Customer Termination

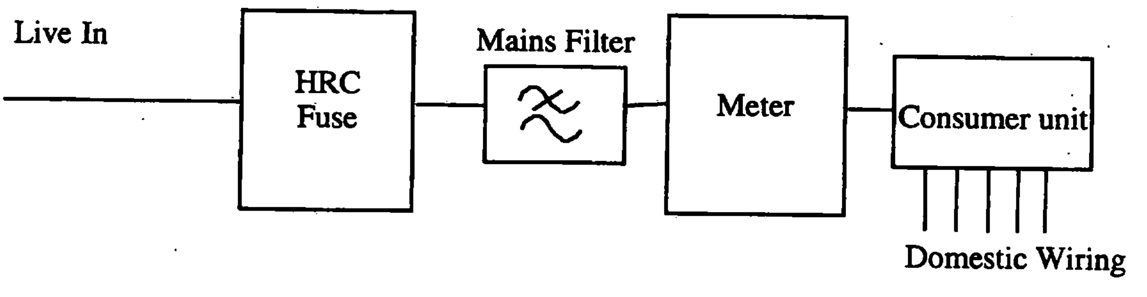

Figure 6.2. Modified Customer Termination

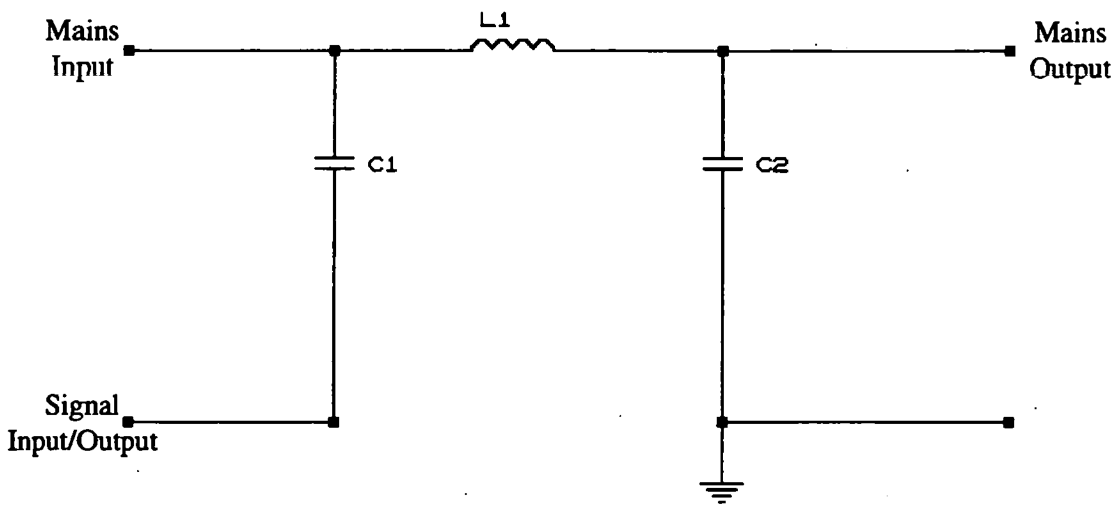

Figure 6.3. Mains Filter Schematic Diagram

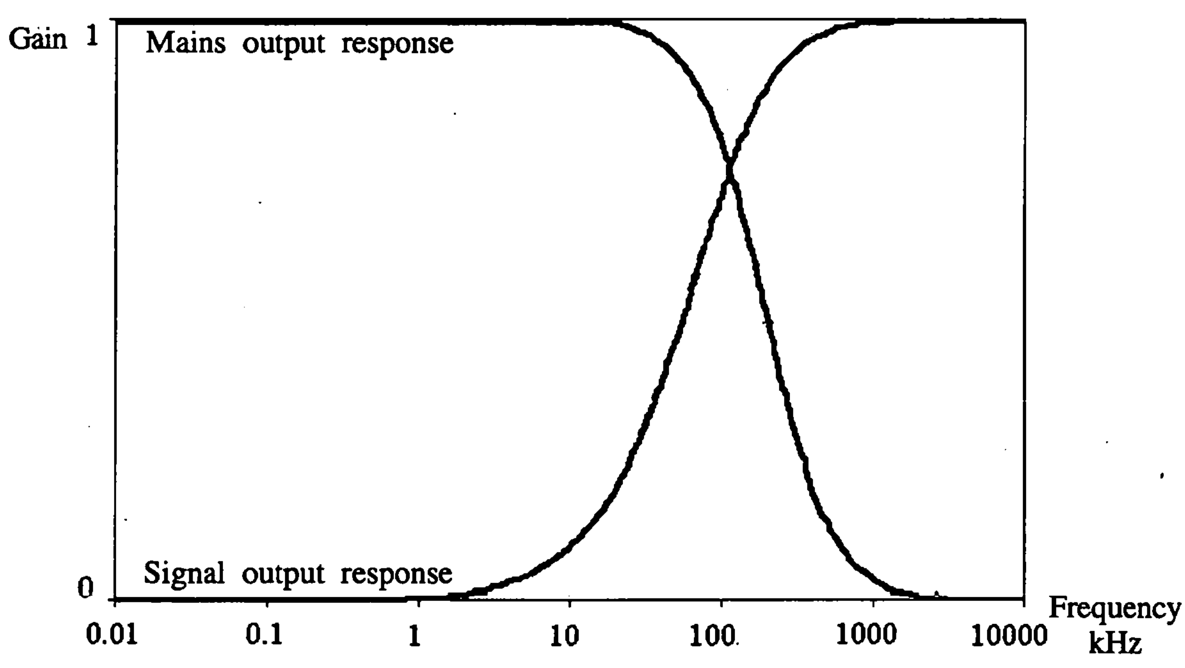

Figure 6.4. Mains Filter response

The components of figure 6.3 perform the functions laid out below.

1) L1. The main inductor for presenting a high impedance to communication frequency (>1 MHz) signals. This inductor must be capable of passing 100 amperes at mains supply voltage

2) C1. Allows communication signals through while stopping power frequency signals. (High pass)

3) C2 Provides further attenuation of the communication signals by shorting to ground, this has no effect on the 50 Hz power component.

At the signal output point is the communication device transmitter and receiver designed initially to present an impedance of 50 ohms to the network.

With the filter and TX/RX installed, the magnitude of the impedance presented to the network when the consumer is drawing 100 amperes (full load) varies between 50.4 ohms at 1 MHz and 50 ohms at 10 MHz, below 1 kHz the impedance looking into the filter is the same as the domestic load.

Any electrical circuit having both capacitive and inductive elements will, at some frequency display a resonance. L1 and C2 will display a resonant frequency, $f = \frac{1}{2\pi\sqrt{LC}}$. In the case of the NORWEB filter the frequency is theoretically 250 kHz. The effect of the resonance is to amplify this frequency. The amount of amplification (Q factor) depends on any resistance present in the circuit. With no resistance the Q factor would be infinite but, as resistance will always be present in any electrical circuit, this theoretical value is never achieved. In this application the Q factor and the resonant frequency will be affected by the consumer load and the network impedance. The network impedance will be fixed as the network is totally conditioned. The impedance magnitude seen by the filter on the house wiring side, varies between infinity (no load) and 2.5 ohms (full load) depending on the power being drawn by the consumer. The higher the impedance of the house wiring (less load) the greater will be this resonant effect. The design of this filter is such that any resonance occurring due to the insertion of the filter is not capable of introducing any undesirable signals onto the house wiring.

The filter as designed has only been tested up to 30 MHz. Above this frequency parasitic capacitance between inductor windings and between other components within the filter cause the filter response to differ from the theoretical response. If the system is to be used for higher frequencies then further testing and redesigning will be required.

6.3 Applerigg test site

The majority of the experimental work carried out during this research was performed at Applerigg, Kendal in Cumbria. This test site is situated on the North side of Kendal about a mile from the town centre. The avenue is supplied with electricity via the Busher transformer from Parkside Road Kendal at 11 kV and this voltage is reduced to normal supply voltage via the Kentrigg transformer situated at the end of the avenue. The outputs from this transformer also supply Kentrigg and Burneside Road with electricity. In total there are 112 single phase supplies taken from the 400 kVA transformer, of which 25 are supplied from the Applerigg feed, see figures 6.5 and 6.7. Permanent access to the network was gained at the transformer and at number 30 Applerigg. The newer supplies on this feeder were terminated in the garage of the house where the supply was required, this made occasional access to customers meters easier and reduced inconvenience for the customer to a minimum.

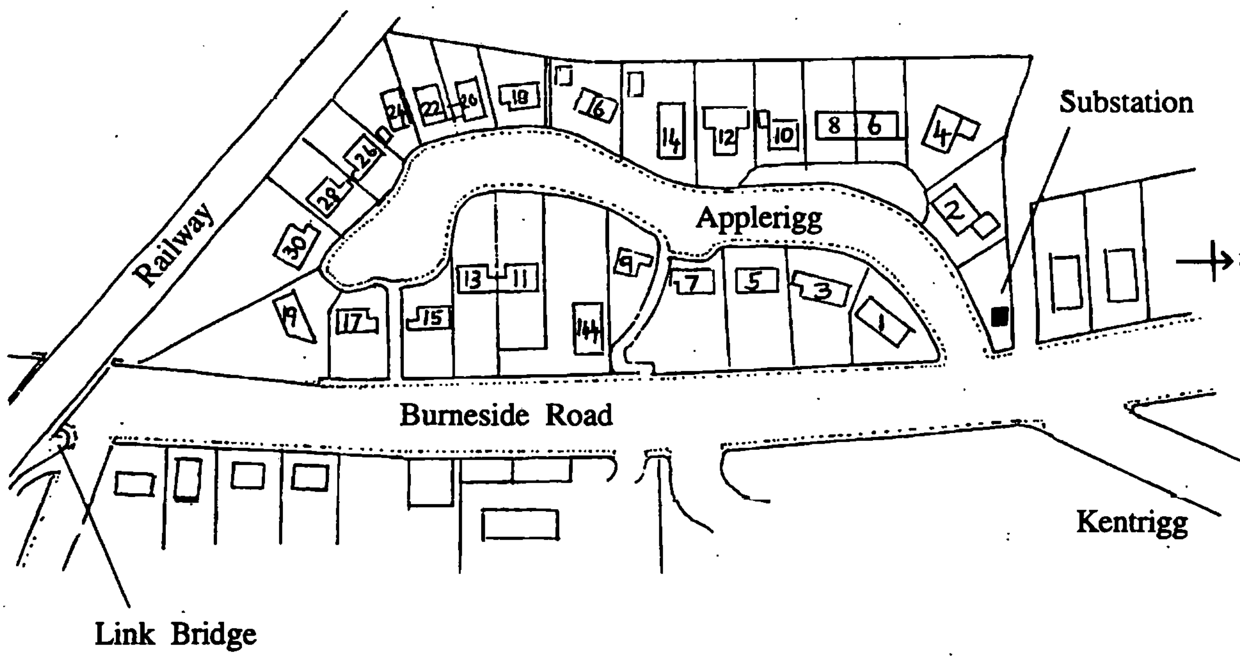

Figure 6.5. Applerigg Map

Permanent access to the network at the substation was achieved by installing a small steel cabin and supplying this with power for equipment and with all three phases of the low voltage supply. This supply was connected to the network on the Applerigg spur as shown in figure 6.6.

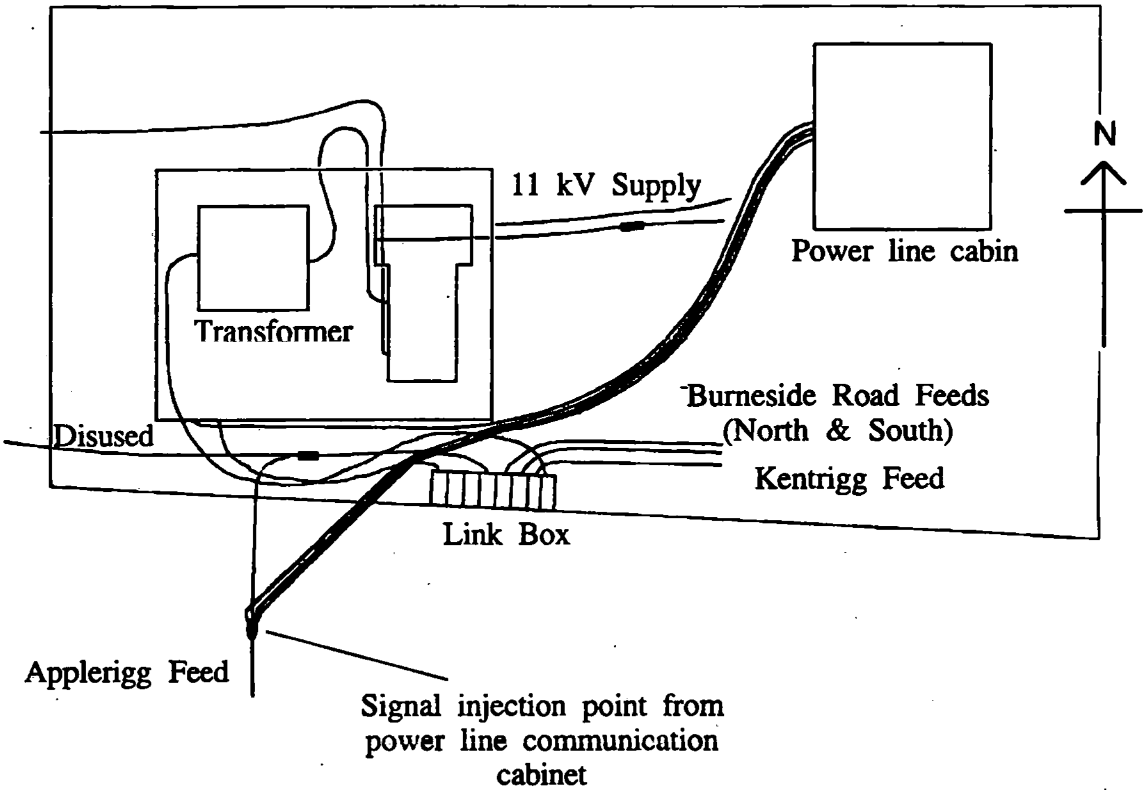

Figure 6.6. Kentrigg Transformer

Access to the network at 30 Applerigg was in the garage, where a shelf was fitted by the meter to hold the equipment being used.

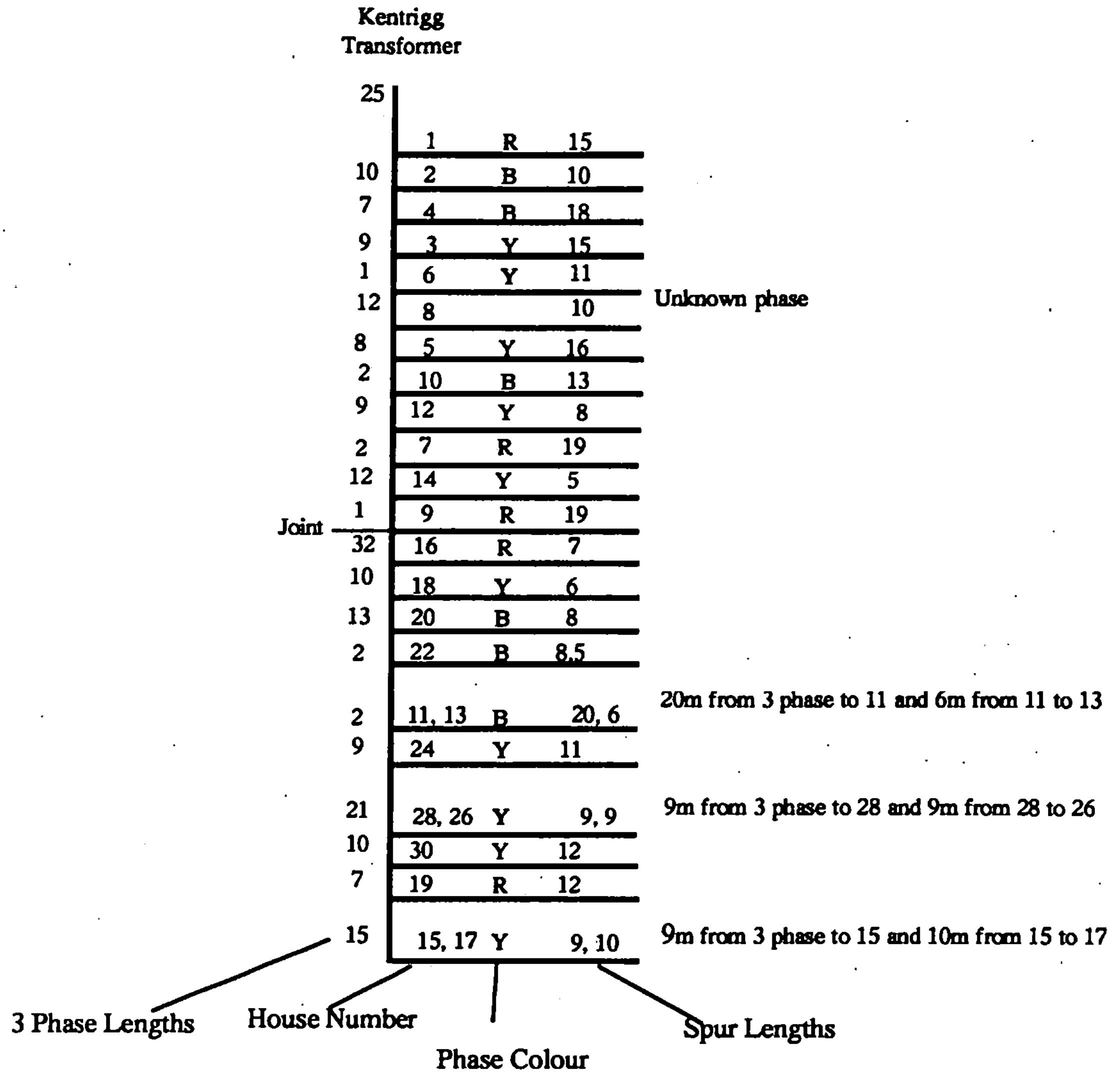

Figure 6.7. Full Schematic of Applerigg

The communication capabilities of the network were tested using ICOM radio amateur transceivers capable of delivering 100 Watts RMS in the frequency range 1 MHz to 30 MHz with an audio bandwidth of 2.7 kHz. With a filter fitted at 30 Applerigg the response of the network was tested by transmitting an un-modulated carrier of known power at the substation and measuring the power received. As each filter was fitted to the houses on the avenue the noise level and attenuation to 30 Applerigg was measured along with the noise level and attenuation to the house where the filter was being fitted. The resident of number 8 Applerigg would not allow access to the equipment at his house so there are no figures for this position on the network.

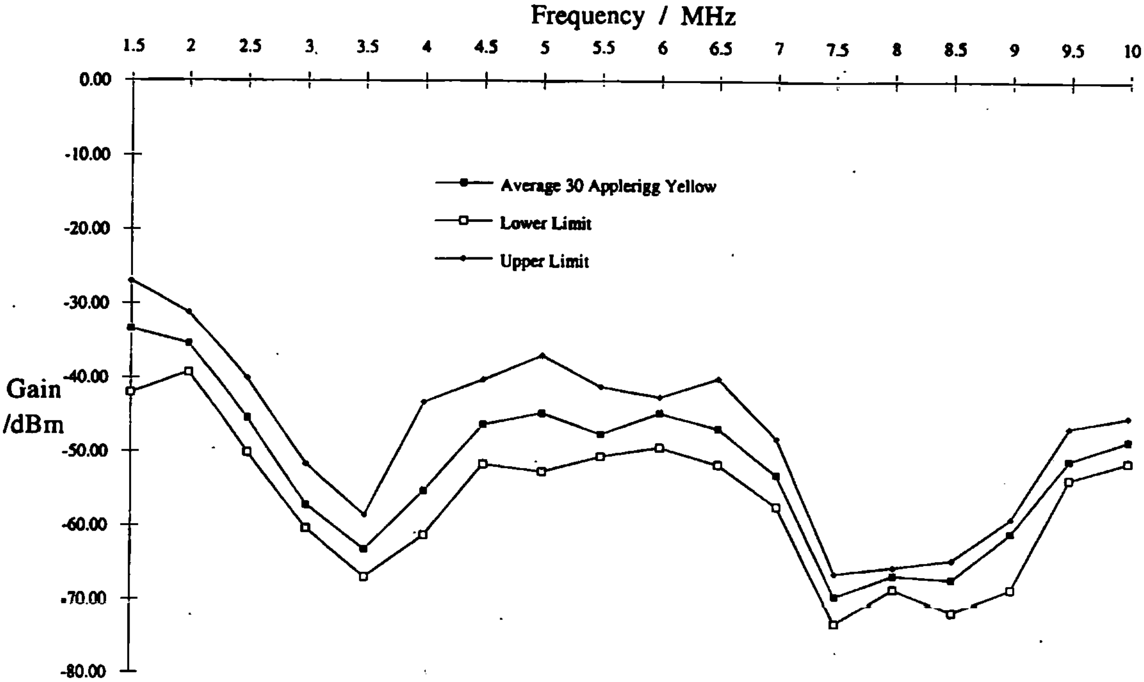

Figure 6.9. The response from the substation to 30 Applerigg.

Figure 6.9 shows the average, upper and lower limits of power received at 30 Applerigg for an injected power of 0 dBm at the substation between the dates 28/8/92 to 28/4/93 on yellow phase with a frequency range of 1.5 MHz to 10 MHz. Before the initial tests there were no figures for the levels of power required for communication over the LV cables. After these tests, transmitted power in the order of one milliwatt to one microwatt were found to provide acceptable reliability. Propagation characteristics were also obtained for the same signal path but using blue and red phases for signal injection, see figure 6.10. These tests showed little difference in received power suggesting that the cross talk between phases is almost 100%. During these tests data could not be obtained for certain frequencies because of the presence of a carrier from some commercial radio stations. These carriers varied in magnitude and frequency with no apparent way of determining whether they would be present or not. If the complete LV network were fitted with the low pass filters these carriers should not vary and any communication system could account for their presence by avoiding their particular frequency.

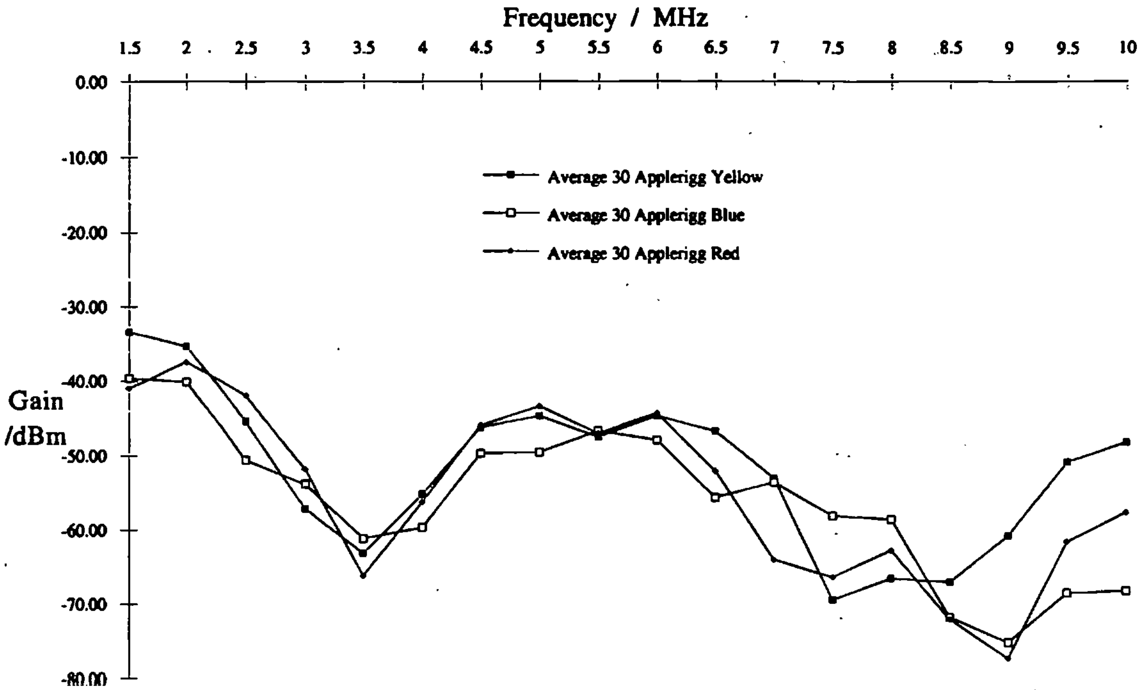

Figure 6.10.

The response from the substation to 30 Applerigg for all phases.

From these results it was becoming apparent that the network was behaving as though two series resonances were present with resonant frequencies at approximately 3.5 MHz and 8.5 MHz. These resonances persisted through all the tests to all the houses, see figure 6.11. The depth of the trough reduced as we approached the substation as did the general attenuation, see figure 6.12.

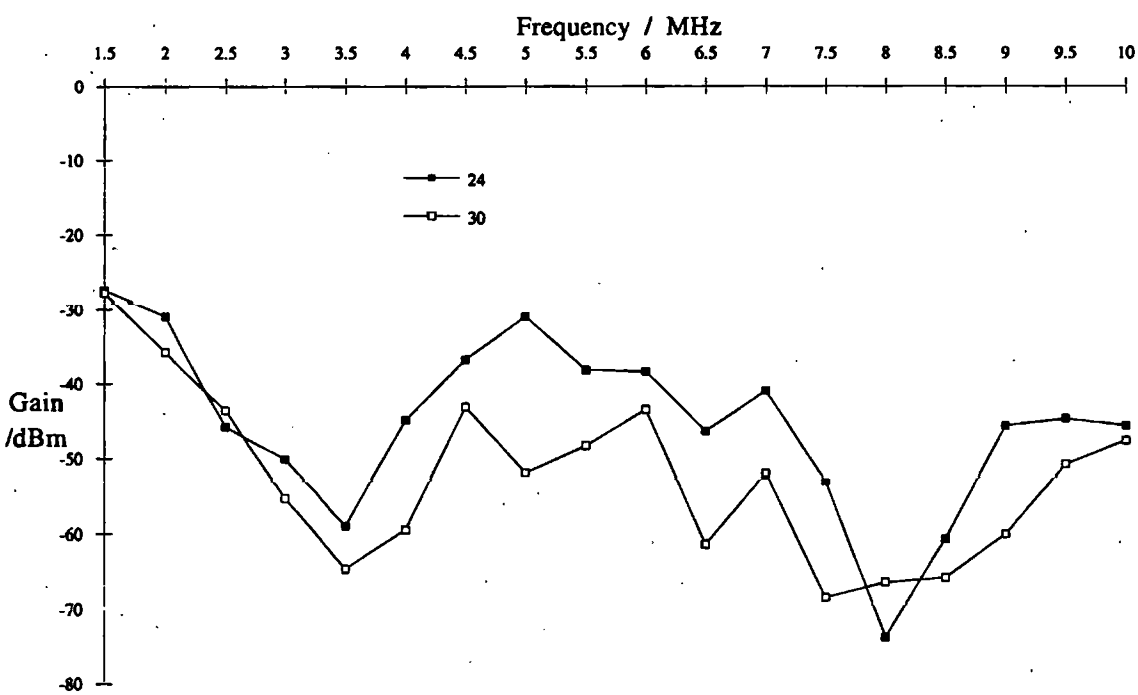

Figure 6.11. Gain to 30 and 24 Applerigg, yellow phase.

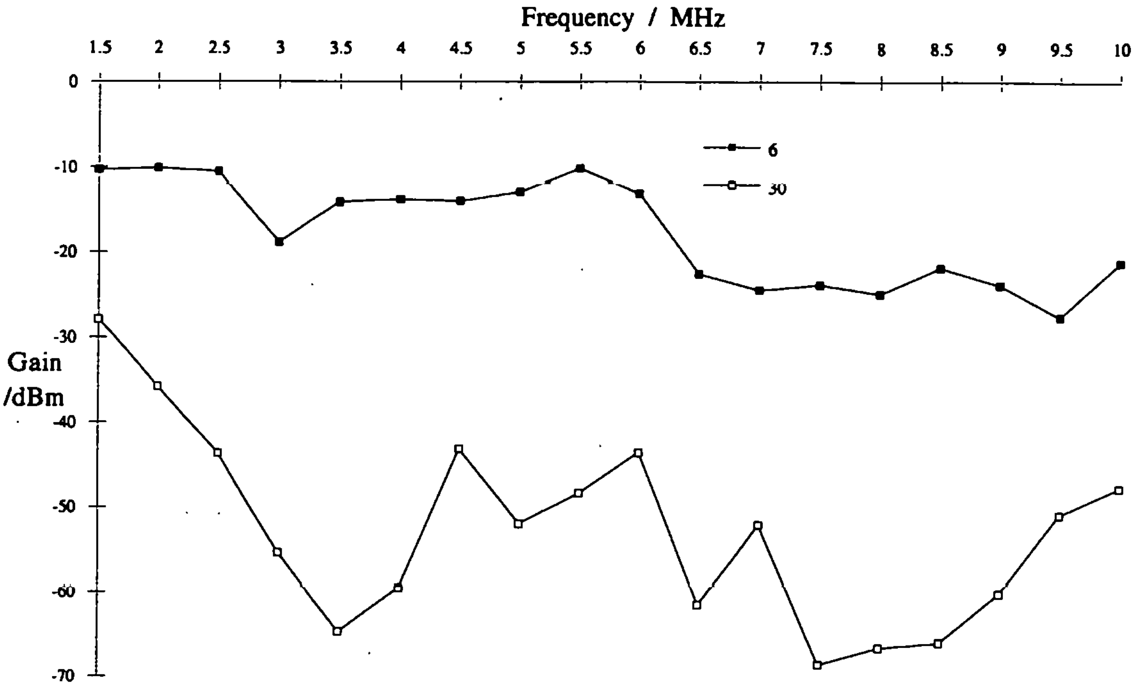

Figure 6.12. Gain to 30 and 6 Applerigg, yellow phase.

The Applerigg spur is the newest of the four spurs from the Kentrigg transformer, it is also the shortest. Access to points on the other spurs was difficult without causing inconvenience for NORWEB customers. There are however normally open link points at the extremes of the Burneside Road South spur and the Kentrigg spur. The link box on Burneside Road is situated by the railway bridge where Burneside Road goes under the railway (see figure 6.5). The attenuation to this point and the attenuation to the Kentrigg link box compared to 30 Applerigg is shown in figure 6.13.

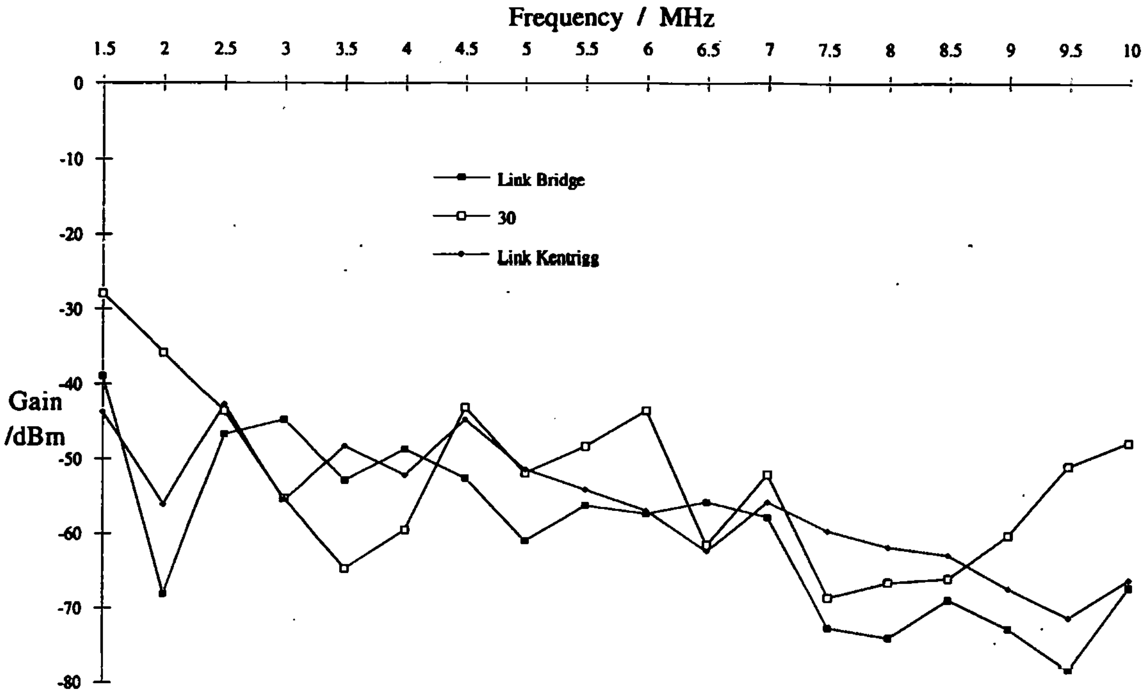

Figure 6.13. Gain to Burneside Road and Kentrigg link boxes and 30 Applerigg.

These link boxes represent the extremes of the LV network from the Kentrigg transformer and show that with an injected power of 0 dBm signals can be received anywhere on the network.

All the previous results were taken during the day with the street lights off. Measuring the attenuation with the street lights off and then measuring the attenuation with the street lights on yielded the results shown in figure 6.14. There are slight differences between the two sets of results but these differences are small and could have been caused by load changes on the network during the time between readings. The time between the two set of results was at least half an hour as the street lights introduce severe noise onto the network during warming up. This takes at least 10 minutes from cold. The noise produced during warm up is so severe that no communications were possible during this period, the power of the noise is inversely proportional to frequency with a level of approximately -30 dBm at 1.5 MHz and disappearing into the background noise floor of -120 dBm at approximately 6.5 MHz.

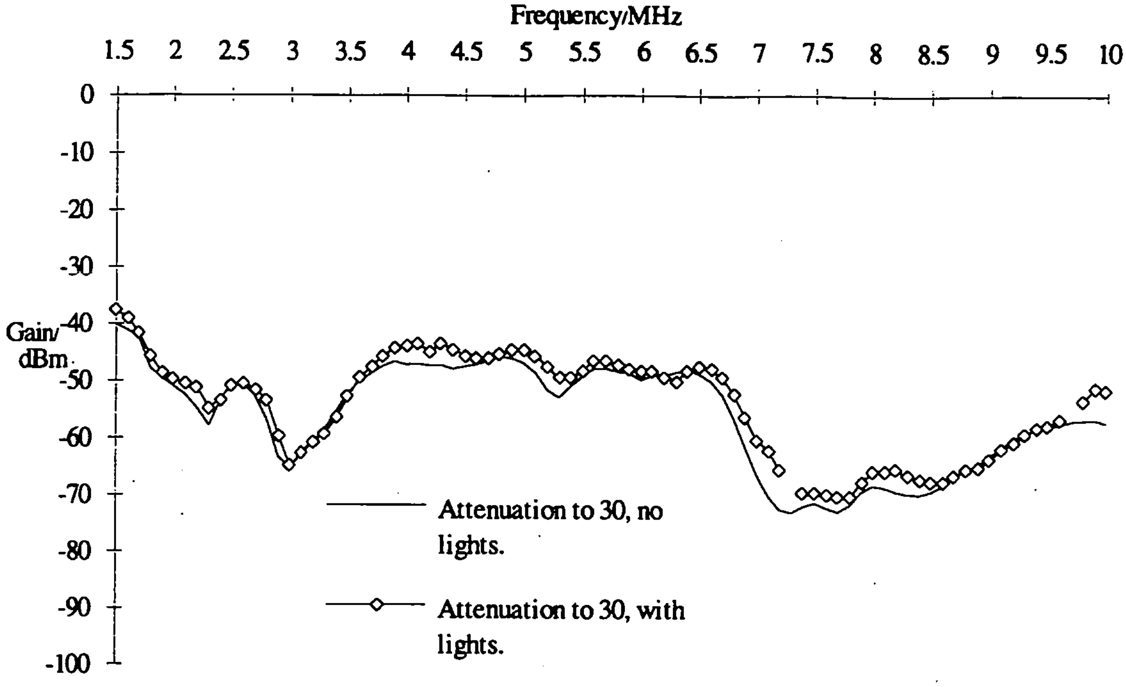

Figure 6.14. Gain to 30 Applerigg with and without street lamps.

The noise produced by the street lamps during warm up totally prohibits communications. In an attempt to overcome this the lowpass filter used for the house termination point was redesigned to provide an in-line filter for street lamps. This filter is rated at 10 amperes and contains no circuitry for signal injection or removal.

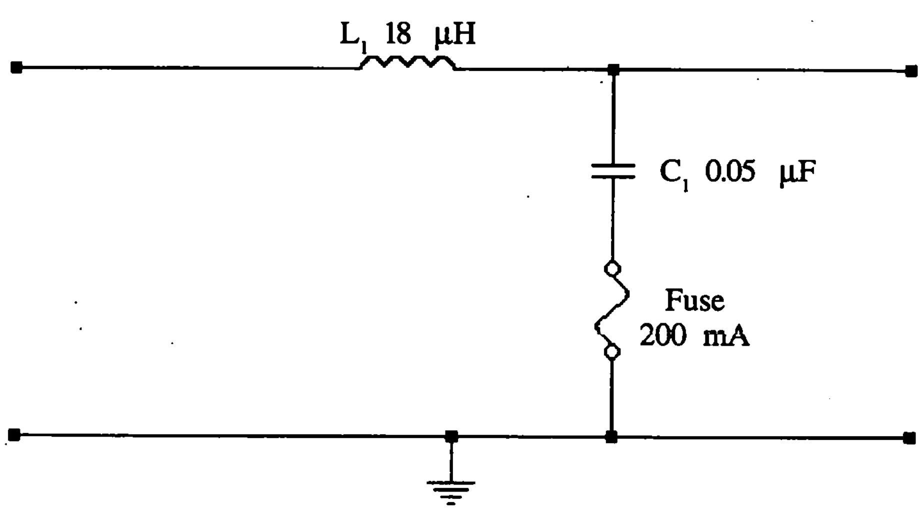

Figure 6.15. Street lamp filter.

The effectiveness of this street lamp filter was very difficult to prove. We could not fit the filter to all the street lamps on the network but did fit six filters to the street lamps on the Applerigg spur. All that could be done to test the filter's capability was to wait for the Applerigg lamps to turn on and measure the noise power at several discrete frequencies with and without the filter. This testing suggested that the filter reduced the noise on the network by approximately 30 dB. The tests were not very accurate because without a person standing at each lamp on the network we had no way of knowing whether other lamps were coming on at the same time. Because the lamps are controlled by photo electric cells they all tended to come on within a short time period. Even with the filter fitted the noise during warm up was of sufficient power to affect most communication attempts.

Having tested the network with an un-modulated carrier several different methods of modulation were tried. All the modulation methods, amplitude modulation (AM), narrowband frequency modulation (NFM) and single sideband suppressed carrier modulation (SSBSC), produced a good communication channel with SSBSC providing the least noise and most clarity, as expected. A commercial communication system using single sideband modulation is not feasible because of the tendency to drift and the accuracy needed in tuning the devices. The final choice of modulation method took into account all the factors for and against each method including noise suppression, power required and cost. With modern frequency synthesis and phase locked loops available in VLSI form cheaply, narrowband FM was chosen as the most suitable. Voice communication between the two provided an idea of the sort of power levels needed to communicate and an idea of the problems introduced when powerful impulse noise was present. With this information it was now possible to run digital tests between the substation and 30 Applerigg.

6.5 Digital testing

The digital testing allowed for continuous tests to be run to ascertain whether or not changes to the communication capabilities of the network occurred at times of the day when voice communication was not possible. Using two PC compatible computers, two Pakrat PK232 radio amateur modems and two ICOM transceivers, the system was setup as shown in figure 6.16.

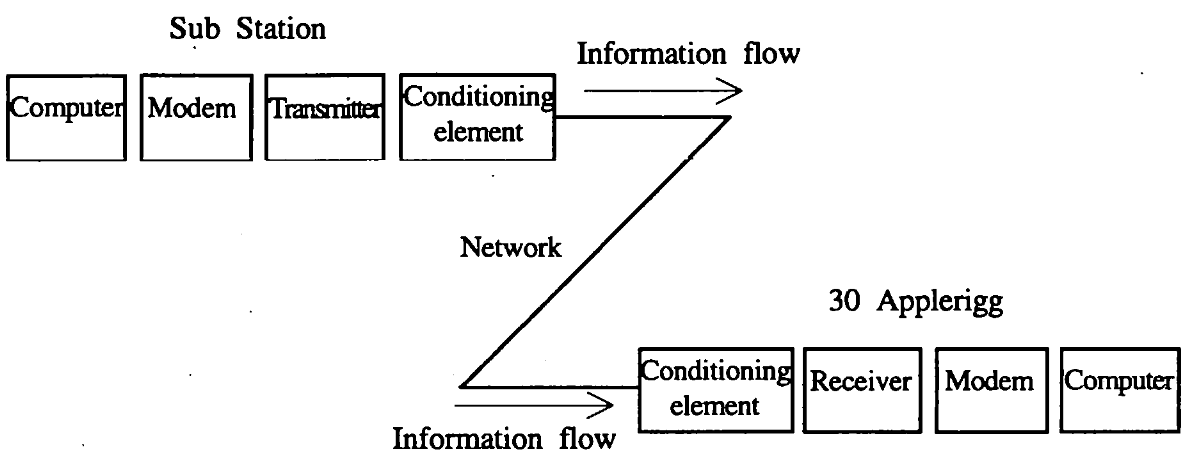

Figure 6.16. Schematic for continuous data tests

Software was written to allow the substation to transmit two ASCII characters continually. The data rates, stop, start and parity bits for the transmission were set by the user. The transmitting end of the installation transmitted 'U' and '*' alternately, this being alternate 1's and 0's in binary. Initially the receive installation was monitored as to the characters being received. This gave an idea of the data rates that should be possible. The most noticeable fact here was that because the modems were being used in ASCII mode and not their native packet mode, at data rates above 300 baud, if synchronisation was lost then the modems would not re-synchronise. This was not a fault of the network but of the modems. This meant that for continuous testing with no supervision the data rate must be 300 baud or less. Before synchronisation was lost, transmission of data at 1200 baud could be received and decoded correctly, 1200 was the fastest speed possible with these modems. With the data rate set to 110 baud using SSB transmission the system logged 935 errors in three days, of these 935 errors approximately 400 were introduced deliberately while determining the cause of errors. Fluorescent lights and freezer thermostats switching in the proximity of the receiving equipment were among the source of the errors.

The error rate for SSB transmission can be compared to the results shown in figure 6.17 where 197 errors occurred for the same data rate, using FM, for a period of 7 days from 6.00 pm 3/11/92 to 12.00 pm 10/11/92.

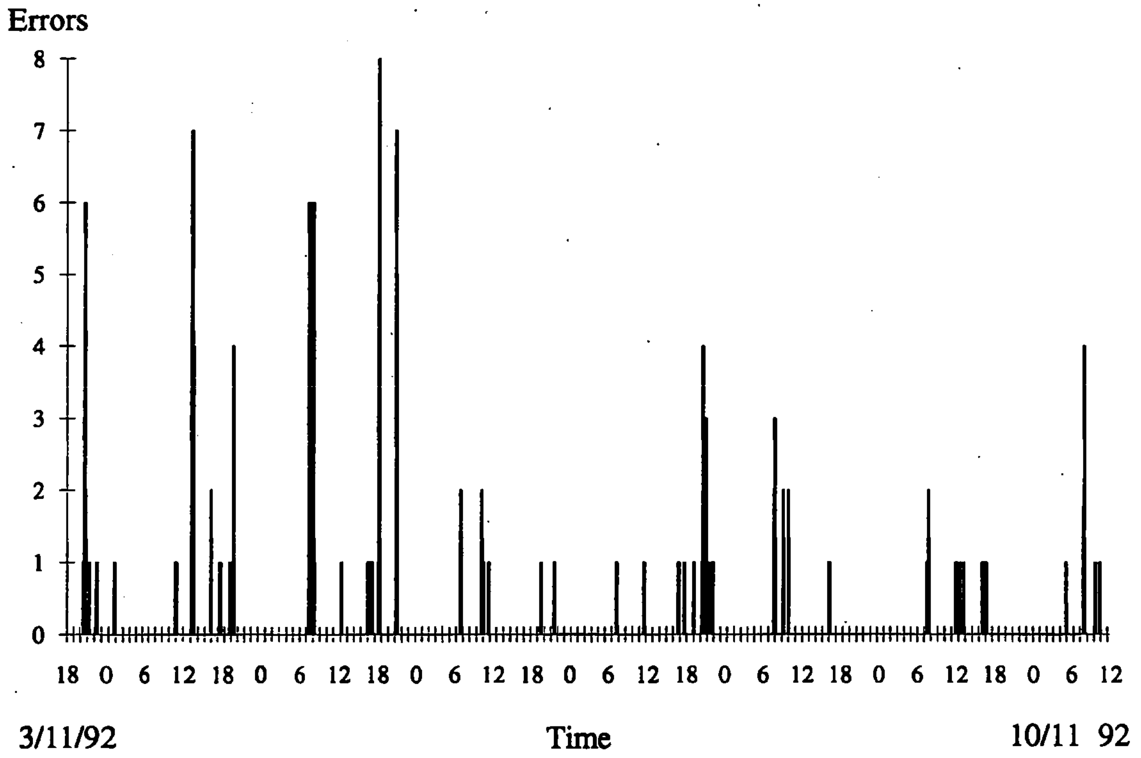

Figure 6.17. Number and grouping of errors, between 3/11/92 and 10/11/92

If the two error files are examined, then where more than one error occurred in the same second, the error characters generally contained the same character string. This points to the synchronisation problem rather than actual data corruption. From the results of these tests uncorrected bit error rates for the channel using FM at 110 baud are estimated to be in the region of 1 in 10^5.

It is not correct from these results to say that the network is only capable of these data rates, this is because the equipment used was never designed for this method of implementation. The modems were designed for the VHF band and for use in packet mode. The results however do show that errors occurred during periods of heavy load, that is, early morning and early evening. It is likely that the errors are down to some daily switch such as central heating or street lamps as they occur at exactly the same time every day. Even though the data rates were low the amount of data that can be transmitted will easily cope with all remote meter reading and load control if this is required.

Having set up a simplex channel the next step was to implement a full duplex channel and interface this to a standard BT phone line. This was achieved by installing a BT telephone line at the substation and by using a Zetron extend-a-line device. This device was designed for allowing a telephone line to cover a large area via VHF radio links in third world countries.

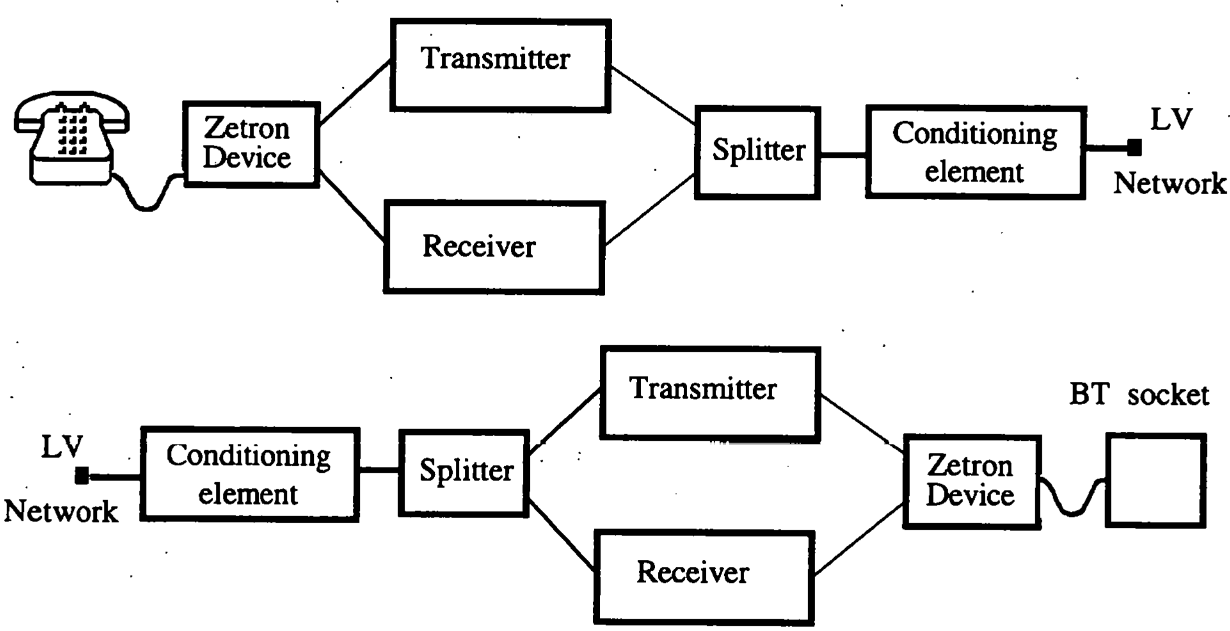

Figure 6.18. Schematic of telephone extension.

It is now possible to use these units directly with no knowledge of the processes involved. If the sub station number is dialled it rings in the garage at 30 Applerigg and a phone call from the garage is made in the normal way. Allowing for the reduction in bandwidth of the ICOM units, 2.7 kHz instead of 3.4 kHz, the quality of the connection is on a par with that of a normal telephone (PSTN) connection with the exception of occasional bursts of noise where the speech may be severely distorted. The noise only occurs in the evenings, the source of the majority of this noise is the street lamps though there is a particular noise burst of an unknown source that will occur on average every twenty minutes. The availability of this facility has been extremely useful as previous testing could only be done when the group was on site, it is now possible to assess the noise levels and transmission characteristics of the line at any time simply by making a phone call.

This telephone facility has also allowed for the testing of the network using standard off the shelf modems for connection to Email and other digital database facilities. The digital communications used previously were not too successful because of the complexity of the necessary equipment and the nonstandard use to which they were being put. With this method the equipment used was employed in a completely standard fashion with methods which are used every day on normal phone lines. Connections have been established via the Applerigg LV network to several bulletin boards at 2400 Baud with no difficulties either establishing the connection or in communication once the connection has been made.

The success in this area proved that the digital problems previously encountered were, as suggested, synchronisation problems inherent in the modems rather than problems with the LV network, the highest data rate previously was 1200 baud and even at this speed an error would result in lost data for a significant amount of time while synchronisation was re-established. At 2400 baud using standard equipment errors only occurred in ones and were no more frequent than could be expected from the same connection using a standard BT line.

Since April 1993 this extended telephone line has been in constant use. The frequencies of operation have been varied between 2 MHz and 15 MHz on both the down link and the up link. If either of the frequencies is below 6.5 MHz then the burst of noise mentioned has interfered with the connection, above this frequency the connection is indistinguishable from a normal BT line. As well as the line being used for speech and modem communications fax communications have been extensively used. No problems other than those mentioned have ever been encountered. If the transmit and receive frequencies are placed closer together than 200 kHz then interference is experienced between the two. In a commercial system using this method, a high Q notch filter at the transmit frequency would be installed in the receive line, this is normal in these type of systems. Because of the constant adjustment in this experiment, fitting a filter would not be practical and it has been omitted. With filters installed adjacent channels could be moved much closer together making one full duplex channel without guard band occupy approximately 6 kHz.

Prior to May 1993 all testing was done at Applerigg. The results suggested that noise and attenuation on the LV network would not prohibit communications though with only the one network tested we had no way of knowing if this was typical or extraordinary. For these reasons several of the substations in Kendal were opened and noise levels on different LV networks were measured. Because the equipment used for these tests needed to be portable and battery operated, the capabilities for measurement were reduced and the noise floor seen on the following graphs relates to the equipment and not necessarily the network itself. Three substations in the Kendal area were chosen for these tests and the tests were run in the 1.5 to 10 MHz range. The results from these tests are shown in figures 6.19 to 6.22.

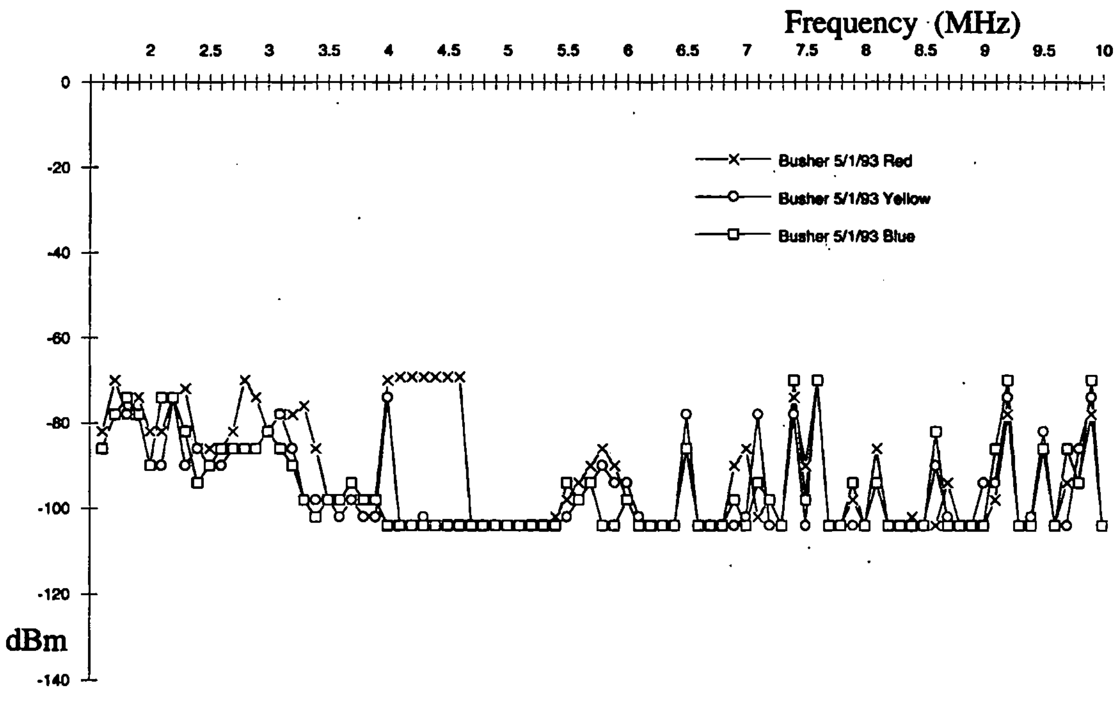

Figure 6.19. Noise levels for Busher transformer Kendal

The Busher transformer in Kendal supplies the police and fire stations, several small industrial sites and some domestic users. It is situated on the edge of the town centre on the North side. There were several very strong carriers present at the time of the tests though they were not of sufficient power to inhibit communications. These carriers are only present for short periods of time, the carrier at 4 MHz on red phase had gone when the readings were taken from the other phases.

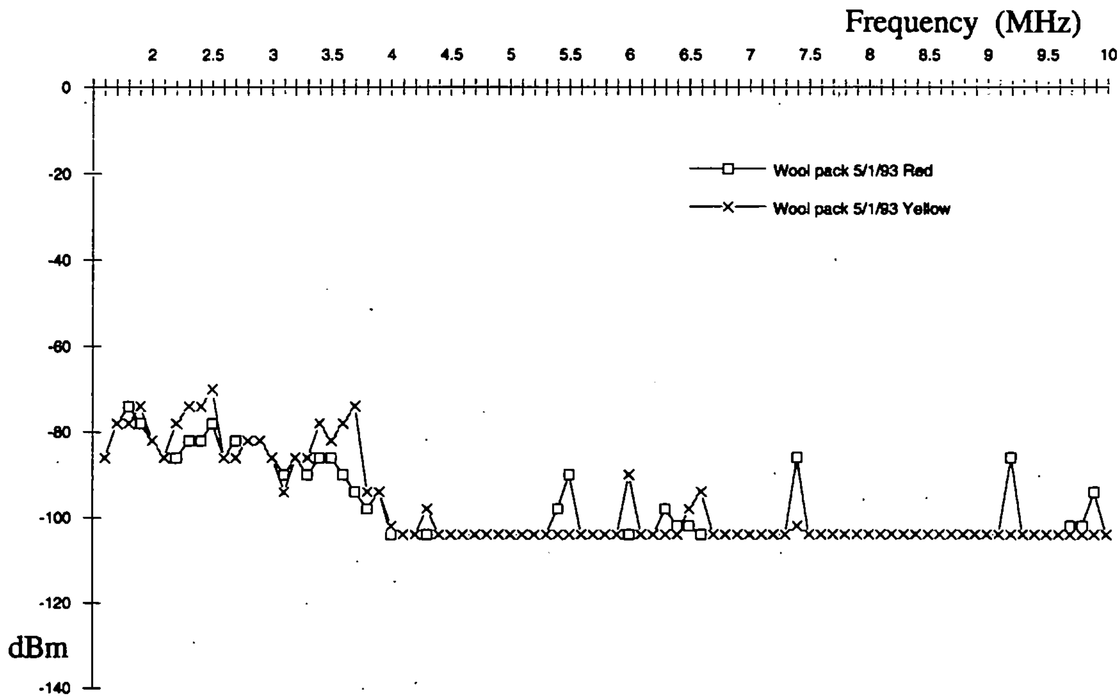

Figure 6.20. Noise levels for Woolpack transformer Kendal

The Woolpack transformer is situated in Kendal town centre to the West of the main street. It supplies the North side of the town centre, this area being mainly small retailers and department stores. The noise levels are similar to those found at Busher without the strong carrier signals. Readings were taken from two of the three phases to save time. The third phase was checked and found to be similar to the others. There were several carriers present but again they were not of sufficient strength to inhibit communications. These carriers can easily be seen on the above chart.

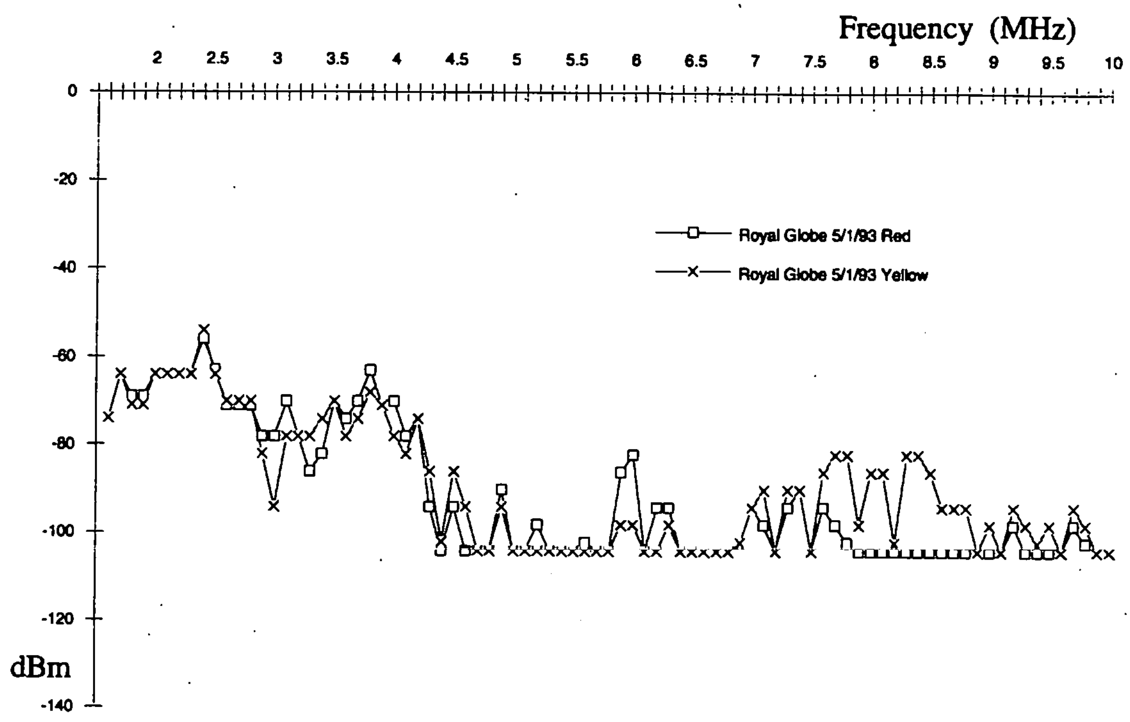

Figure 6.21. Noise levels for Royal Globe transformer Kendal

The third site chosen for the tests was again in the centre of Kendal. The Royal Globe supplies the South West side of the town centre, this area has more residential supplies than the other two and has some hotels, theatres and museums. The most significant feature is that the noise is at a significantly higher level. This may be a characteristic of the network or it could be because of the time of day. Although we tried to take the readings in as short a time as possible there was still some 90 minutes between these readings and the ones for the Busher transformer. The readings for the Royal Globe transformer were concluded by 13:30.

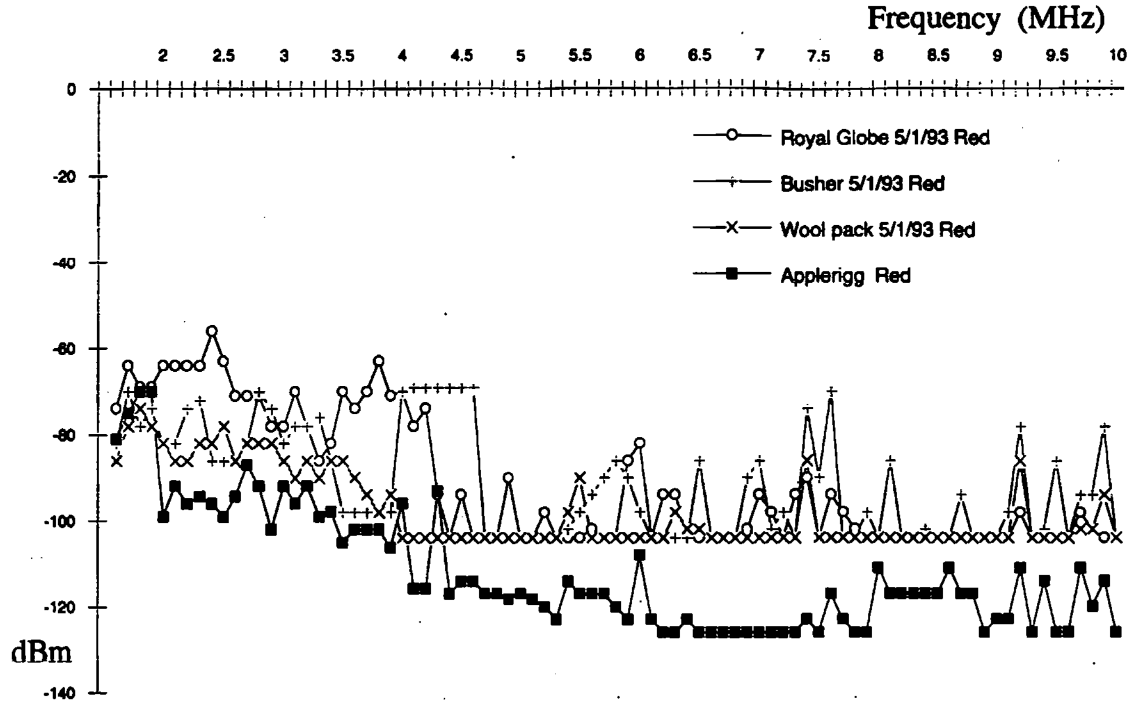

Figure 6.22. Noise Levels on Applerigg Compared to Other Networks

The noise levels for the town centre networks are significantly higher than the figures for the Applerigg network. This was expected for two reasons. The network activity in the town centre will be greater than Applerigg due to the different geographical location of the networks and the Applerigg transformer and test facility is entirely contained within screened, earthed, steel boxes whilst the substation sites within Kendal are all contained within brick or stone buildings with open bus bars and no screening. The connections used for these tests were achieved by way of a clip connected directly to the open bus bar. With no screen the bus bars present very efficient aerials to any radio frequency signals.

The background noise level is not strong enough to prevent communications though the strong intermittent carrier signals would cause problems in an analogue situation and errors in any digitally transmitted data. These problems would be significantly reduced if the networks were conditioned, but they can be tolerated without conditioning if data can be error checked and re-transmitted. The Applerigg data was not subject to the -106dB minimum resolution of the town centre sub stations because this data was collected from non portable equipment installed at Applerigg

6.6 Chorley Test Facility

At the end of 1993 NORWEB installed a low voltage network at their Chorley training centre for the purpose of research into communications. This LV network was based on the average network with 50 single phase supplies including 6 street lamps, see figure 6.23. Each of the supplies is terminated in a small box fitted with an HRC fuse and the conditioning unit for signal injection/recovery. The first six supplies from the network are fed back into a steel cabin at the network origin and the last three supplies are fed back into a small steel cabin at the end of the network. The main three phase feed into the network is from the larger of the two huts and from this point can be easily connected or disconnected from a live supply. Up to now the street lamps have always been disconnected by removing the fuse in the base of the street lamp. With the completely open access we have to this network any tests can be performed with no inconvenience to any customers. From start to end the network is 250 metres long. Whilst the network was being installed an 11 kV three phase cable and a 33 kV single phase cable were laid from end to end along the network. These cables are continuous having no joints or spurs.

Testing of the network started in March 1994 and the tests followed the same methods used at Applerigg. Each of the signal injection points on the spurs was terminated in a 50 ohm resistor which was removed from a particular spur when communication tests to that spur were carried out. Characteristics of the network were similar to Applerigg with the exception of the 'characteristic shape' of the response. On Applerigg the 'W' shaped frequency response had been similar across all of the network including all three phases. At the Chorley network each phase had it's own characteristic response with a very high attenuation at 2 MHz being the only part of the response that was common to all three phases. Attenuation and noise results were taken with the network live and dead. Above 1.5 MHz there was no difference in the results. This implies that noise on the network does not come through the transformer.

During this research there was no work done on transformers though it appeared that the transformer was of high impedance looking into the secondary windings because of the lack of change to the response when the transformer was connected.

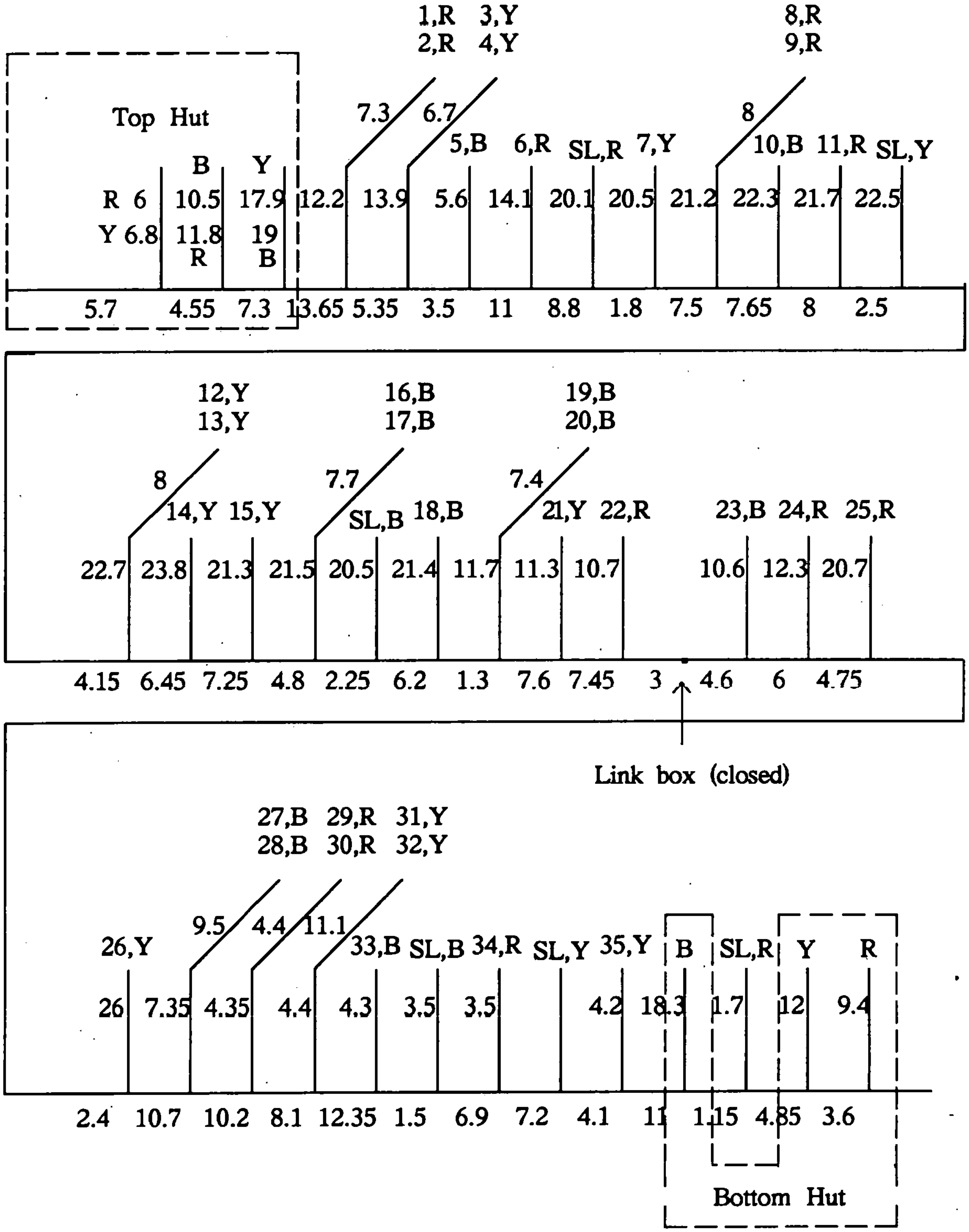

Figure 6.23. Chorley experimental network schematic.

The figures 6.24 through 6.28 show sample responses from the Chorley test network. Where relevant, they are referenced to 0 dBm injected at the network origin.

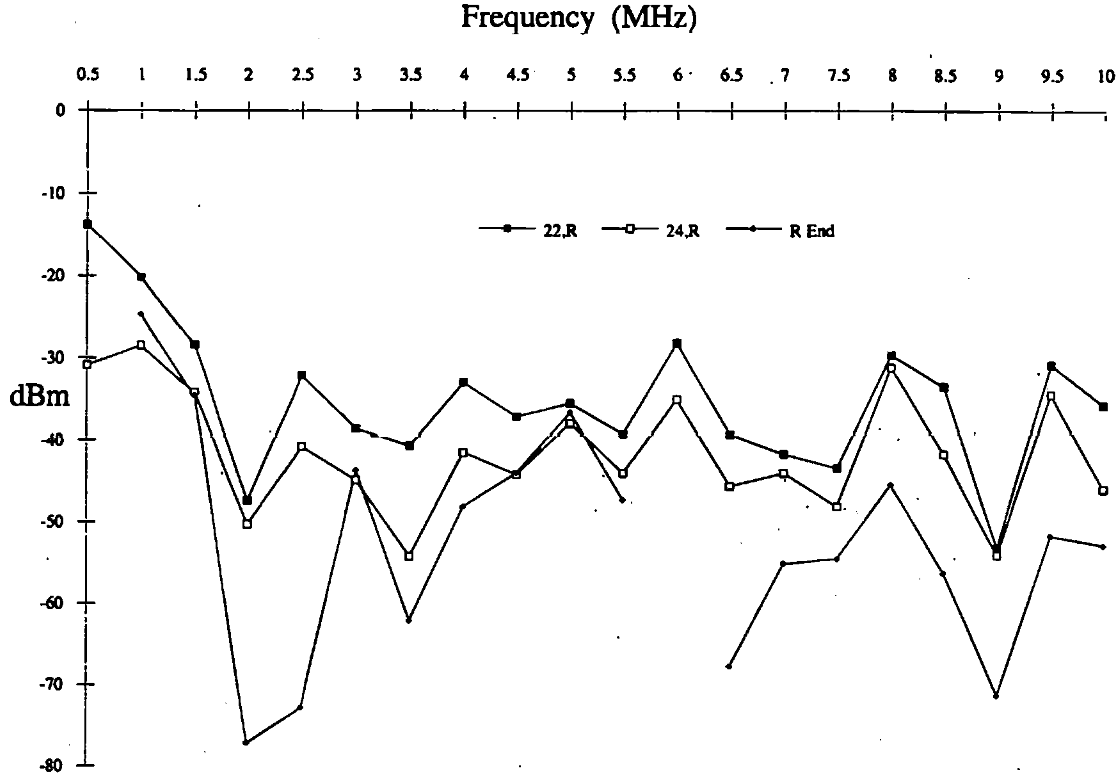

Figure 6.24. Sample response, red phase

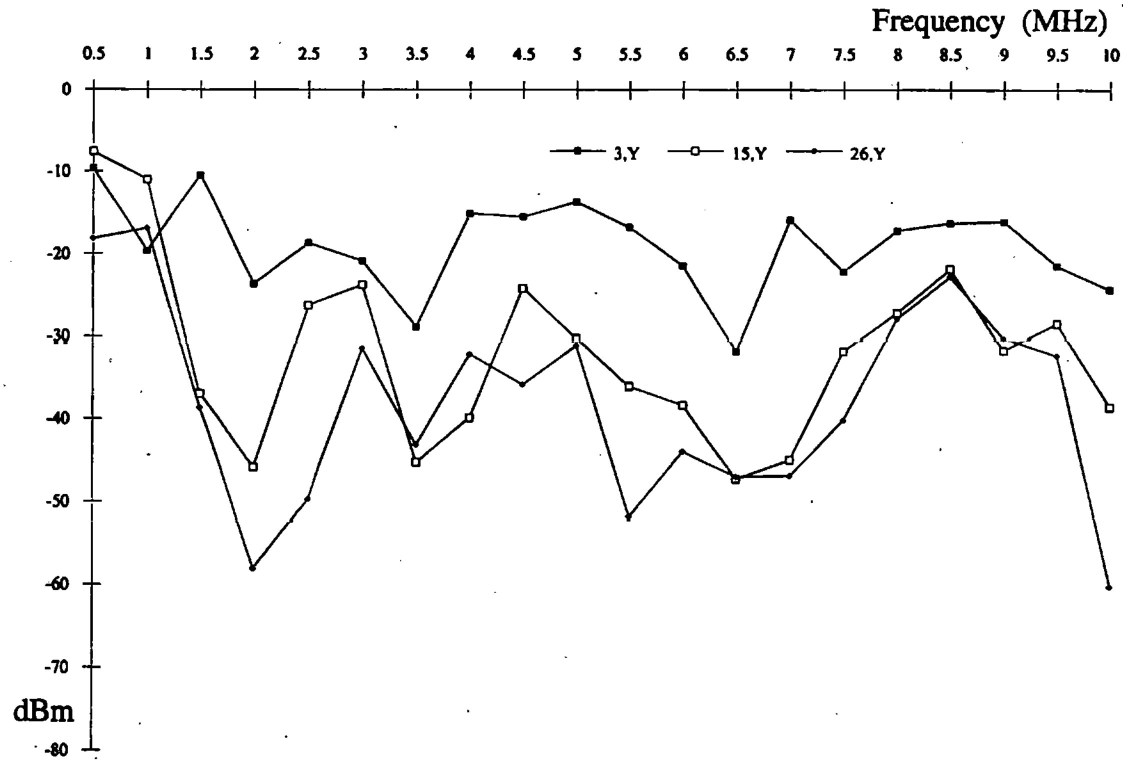

Figure 6.25. Sample response, yellow phase

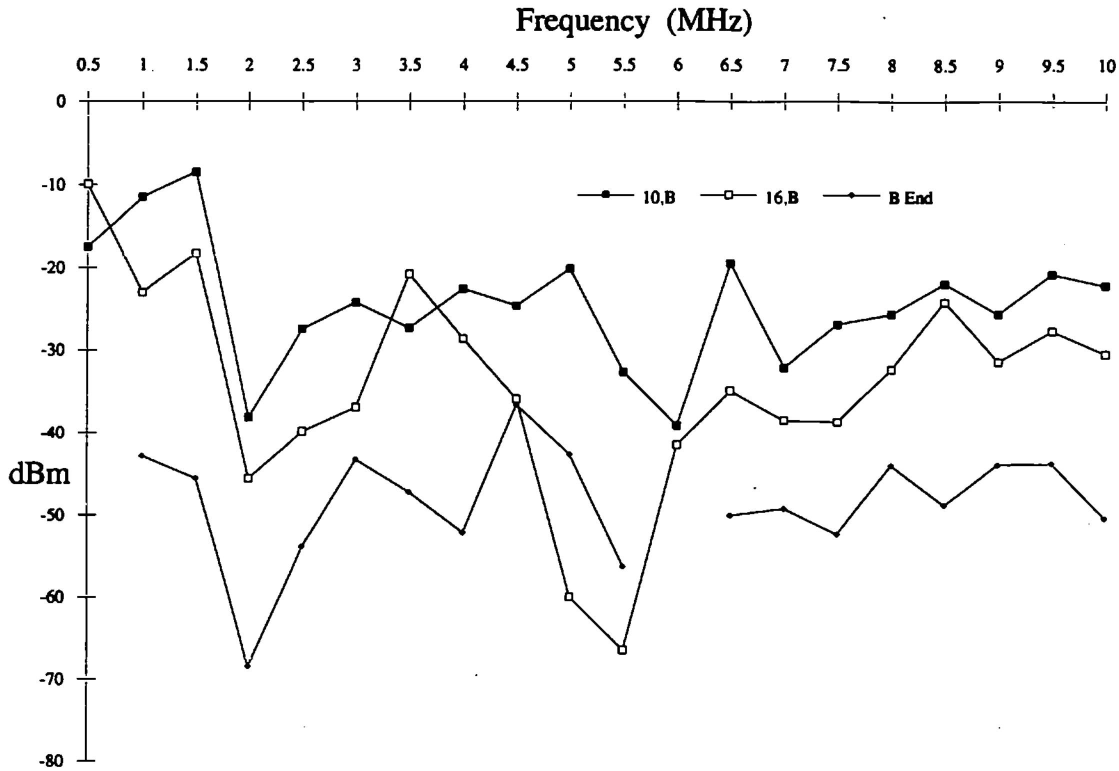

Figure 6.26. Sample response, blue phase

The test site at Chorley is located within sight of Winter Hill. This location is the site of many transmitters spread throughout the radio spectrum. This resulted in several strong carriers being present when samples of the background noise were taken from the network.

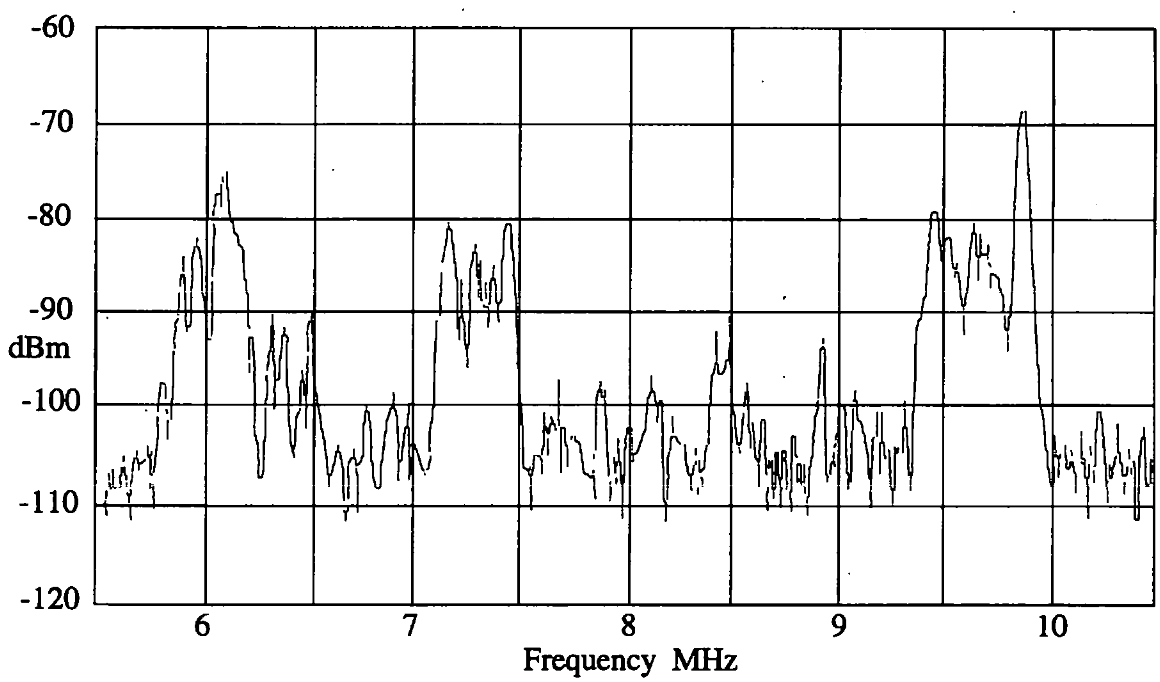

Figure 6.27. Sample background noise. Red phase, 5.5 to 10.5 MHz

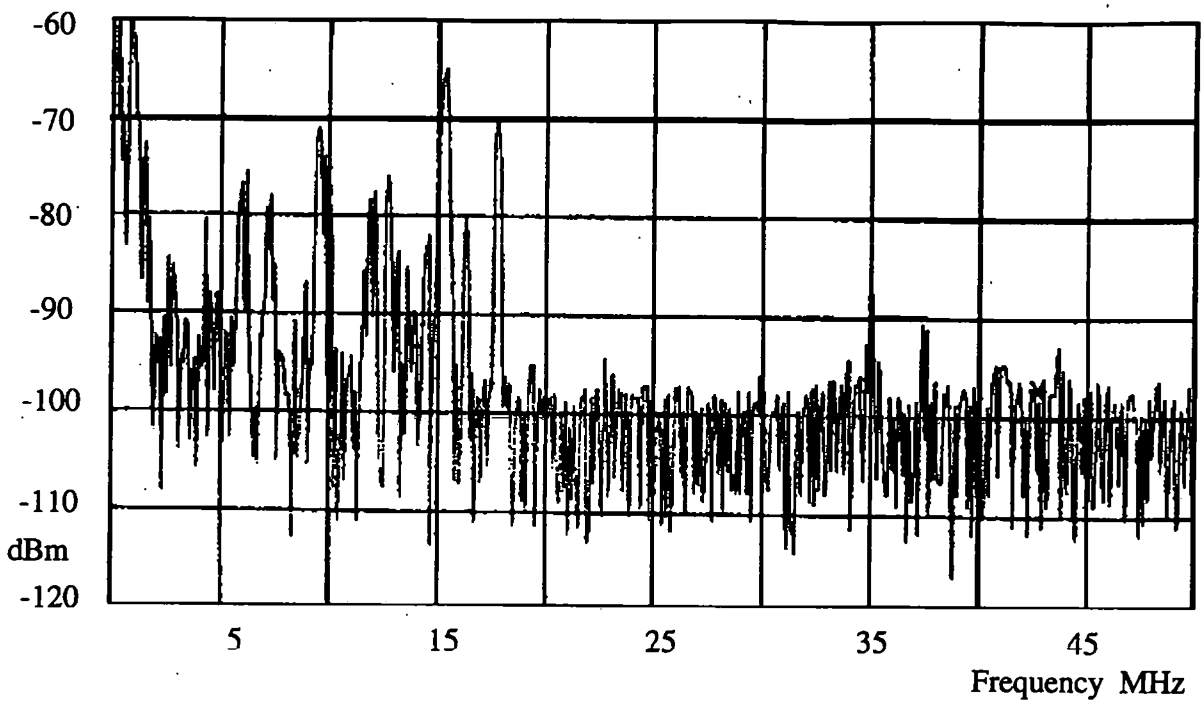

Figure 6.28. Sample background noise. Red phase, '0' to 50 MHz

As with the Applerigg network and the other networks in Kendal there was nothing to prevent communications on the Chorley network. The response was similar though again it had a characteristic response shape that remained the same no matter what equipment or loads were present. This fixing of the frequency response of a network is one of the more important points to arise from conditioning the network with filters.

6.7 Summary

The two test sites have provided a tremendous amount of practical information about the practicality of using the LV networks for communications. Because of the completely open access of the Chorley network NORWEB were able to commission some very specific testing from external research sources. These included radiation tests, Dect standard transmissions and modified CT2 standard transmissions. This research continues and NORWEB are currently testing different injection, modulation and coding methods on different networks throughout the NORWEB area.

A technical trial site in Manchester has been set up to provide telephones for 20 people on one LV network, using the CT2 standard, this site has been running for approximately 12 months. The next stage in this development is a marketing trial, again in Manchester. The site for this is being investigated and it is hoped that the trial will be running by mid 1996.

Chapter 7. Conclusion and Further Work

This thesis shows one method for calculating the response of any single or multi phase cable or distribution network where the TEM wave is the method of propagation, providing there are no closed loops within that network. The methods employed necessarily include some approximation of parameters. These approximations have been justified by comparisons between practical and theoretical results.

The practical work done in the course of this research has provided a significant new field of research for power line communications in the area of the HF radio spectrum. There is still a substantial amount of work to be done in this area before the subject can be fully understood. This thesis provides a theoretical approach to the distribution system with an in depth look at the networks used and there propagation characteristics. The comparisons between theoretical and practical results show the methods to be valid though the approximations made mean that inaccuracies are present in these results.

With further work the number of approximations can be reduced, giving a significant increase in the accuracy of the answers. The areas most in need of further research are as follows.

1) The depth of analysis given to the calculation of capacitance could be repeated for the inductance of the cables. The effect of the inductance on propagation and the variation of inductance with physical cable changes is not as great as the effect and variation of capacitance, but the results would certainly be more accurate if equations for inductance were developed using similar methods.

2) Given that the skin effect on resistance is dependent on the areas of current flow, the resistance value could be approached with a view to accurately defining these areas within the cables. The methods employed at present assume a fairly straightforward current path based on basic geometry. A thorough analysis using conformal transforms and/or finite elements may reveal current paths and propagation characteristics not thus far envisaged.

3) The effects of current migration through the screen of the cables because of induced magnetic fields has not been approached at all in this thesis. An investigation in this area may reveal that the current paths within the cable are not as anticipated here. A necessary part of this investigation would be a thorough analysis of the supply joint at the substation, the methods of joint manufacture within networks and the methods of terminating the power supply before the conditioning units. These points will all affect the propagation of signals on the network.

4) The effect of the supply transformers has not been researched. From the results obtained it was thought that the transformer was of reasonably high impedance but that the distribution point within the substation was of low impedance. This area is of sufficient complexity to need researching as a separate subject.

5) Though the methods shown can be applied to overhead cables it was the intention of this thesis to develop methods for underground systems. Overhead systems differ significantly from underground supplies in that any communication methods could be presented with a balanced rather than an unbalanced system and would tend to be point to point rather than being a tree and branch network. This means that even though the conductors are unshielded, the effect of being a balanced system should mean that the cables do not radiate provided the terminations are of the correct impedance. This is an area that is currently being investigated by NORWEB.

6) As part of the multi phase solutions shown here it is necessary to find the square root of a three by three matrix. The method shown is normally successful but in certain circumstances this method can be made to fail. This occurs when two of the roots produce sensible, positive answers preventing the software from rejecting the huge, negative or zero values as incorrect. The process has been tried with several values and this problem only occurred when artificial values were inserted in the matrix. In all cases where actual cable values were inserted in the calculation the roots produced only one sensible answer. It is considered that this is the weak point in the series of calculations and another method of solution either not involving square roots or involving another method of root solution would be more stable.

7) Noise on these networks in the HF band does sometimes present a problem. This area would warrant an in depth investigation which would produce information on the most bandwidth efficient modulation and coding techniques to use.

Appendices

Appendix 1	Results of an INSPEC search into current and past power line signalling systems.
Appendix 2	Data entry programme software listing.
Appendix 3	Calculation programme software listing.

Appendix 1

Bibliography

The following is a bibliography obtained by means of an INSPEC database search on the past 4 years record. The keywords used were "mainsborne", "mains", "signalling" and "communications". These search results are reproduced courtesy of NORWEB.

Where language is not indicated, it is English.

INSPEC 3431389 B89059157 Title: A multi-function distribution system for advanced offices

Journal: Elettrificazione

Iss: no.4 p. 121-4

Date: April 1989

Language: Italian

Abstract: The article describes a new system of trunking suitable for power, communication and data processing cablework. The design is adaptable to rising mains, ceilings, walls and floor fitting, and includes a comprehensive range of outlet connectors. (0 Refs.)

INSPEC 3423639 B89050533 C89049023

Title: Data transmission over electricity mains network

Journal: NTZ

Vol: 42 Iss: 4 p. 242, 244

Date: April 1989

Language: German

Abstract: The electricity mains network is suitable for information transmission in the 85-145 kHz range. A block diagram is shown of the ASK modem with the NE 5050 integrated circuit which provides both sending and receiving facilities and some interference suppression for data transmission over the electricity supply network. Various possible uses are mentioned and a hotel pay-TV system is briefly described. (0 Refs.)

INSPEC 3419751 C89047555

Title: CEBus: US households are being networked

Journal: Funkschau

Iss: no.9 p. 45-7

Date: 21 April 1989

Language: German

Treatment: Practical

Abstract: CEBus stands for Consumer Electronics Bus, a standardized communications interface for operations by telephone, timer or remote control brown and white wire in a household over 4 types of carrier: mains supply, twisted twin wire, coaxial cable and infrared beam. Information is given on the work of the CEBus commission of the American EIA, on 17 firms participating in a recent dedicated exhibition, on DIY systems, pioneered by Radio Shack and on the rival organisation AHBA (American Home Builders Ass.) with its 'Smart House' concept. (0 Refs.)

INSPEC 3417116 B89050535

Title: Power line modems and networks

Authors: Broadbridge, R.

Conf. Title: Second IEE National Conference on Telecommunications (Conf. Publ. No.300) p. 294-6

Publisher: IEE

London, UK

Date: 1989 xi+431 pp.

Conf. Date: 2-5 April 1989

Conf. Loc: York, UK

Abstract: A look at the history, present applications and system designs for mains-borne data communications. Modem selection and networking software are covered. (0 Refs.)

INSPEC 3395350 B89045925 C89037349

Title: A spread spectrum communication system for load management and , distribution automation.

Authors: Hagmann, W.

Affiliation: Brown Boveri Res. Center, Baden, Switzerland

Journal: IEEE Transactions on Power Delivery Vol: 4 Iss: 1 p. 75-81 Date-Jan. 1989

Abstract: Based on a discussion of channel characteristics and the design objective of a high overall link availability, it is shown that a frequency-hopping communication system using phase-shift-keying modulation can overcome the problems of the more traditional narrowband communication systems. The design parameters of such a system are then discussed. The performance is evaluated, and results of measurements in testbeds and on the power mains are presented. (16 Refs.)

INSPEC 3393134 B89044221 C89041072

Title: The future: the intelligent house

Journal: Funkschau

Iss: no.3 p. 45-6

Date: 27 Jan. 1989

Language: German

Abstract: Reports on the concerted Japanese efforts to establish standards for a domestic bus rail system for the house of the future is supported by a schematic diagram of such an intelligent house. Security (intrusion, smoke and leakage detectors), domestic services and appliances for heating, air conditioning, water and lighting, interactive information services with computer and copier (banking and shopping, data) and electronic entertainment (radio, Hi-Fi, terrestrial and satellite, video recording) are operated and monitored via a main bus- and several sub-bus rails. In use are coaxial cables, twin wires and mains, carrying tone burst signals. (0 Refs.)

INSPEC 3365350 B89033300 C89033180

Doc Type: Journal Paper

Title: Bits from the power point. IC for data transmission via the mains

Journal: Elektronikschau

Iss: no.2 p. 48-50

Date: Feb. 1989

Language: German

Abstract: The mains power wiring can be used as a data transmission medium over short distances, such as within a building. The author describes the modem IC NE 5050 from Philips which uses this method of communication A data rate of 1200 bits per second is envisaged. The modem uses amplitude shift keying of a 100 kHz carrier. (0 Refs.)

INSPEC 3353969 B89032719

Doc Type: Journal Paper

Title: Universal data transmission. Economical over great distances

Journal: Funkschau

Iss: no.26 p. 68-9, 105-7

Date: 16 Dec. 1988

Language: German

Abstract: Further to the description of a modem for data transmission over mains cables, (see ibid., no.18, p.65, 1988), ICs of the PED 15 series, intended for data transmission and reception, are introduced, supported by diagrams of circuit configurations, build around the PED 15 for transmitting and for receiving modes, waveforms used in both modes, and a table of pin connections and associated functions. DIY designs of two different transmitters and two receivers are then described in detail, typical applications being: a 15-bit electronic lock; parallel data transmitter; 8-bit serial transmitter to up to 128 addresses; and telemetry interrogator. Block- and circuit diagrams, printed board drawings and a parts list are provided. (0Refs.)

INSPEC 3342719 B89021881 C89025433

Title: 220 V mains data bus which has VdS approval certificate (burglar alarm)

Authors: Bormann, M.

Journal:

Elektromeister & Deutsches Elektrohandwerk

Vol: 63 Iss: 21 p. 1467, 1471

Date: Nov. 1988

Language: German

Abstract: Describes the VICOM III burglar alarm system where the individual switches and detectors communicate over mains wiring in domestic installations, using time multiplex. Filtering against the external power supply system is offered, and it is suggested that mains wire signalling can be combined with signal wire signalling. (0 Refs.)

INSPEC 3270341 B89004541

Title: Mains modem-220 V as a remote data transfer medium

Journal: Funkschau

Iss: no.18 p. 65, 67, 93-5

Date: 26 Aug. 1988

Language: German

Treatment: Practical

Abstract: A simple DIY modem is described which joins other, mainly telemetering appliances, in transmitting on long waves (here 100 kHz) over mains. The core of the modem is the special Valvo IC NE 5050, which contains an amplifier, buffer, power driver, 100 kHz carrier generator and flip-flop output stage. ASK (amplitude shift keying) is applied, not FSK as in most acoustic couplers. The use of an additional IC (RC 4151) as a voltage/frequency converter extends the application field to many telemetric sensors. (0 Refs.)

INSPEC 3693010 B90058829

Title: Communications technique for remote meter reading

Authors: Cerami, P.; Orsenigo, E.; Sergi, R.

Journal: Power Technology International

p. 307-8

Date: 1989

Abstract: ENEL has decided to use electronics technology for low voltage remote management systems. In 1986, the utility put out a tender for interested companies to participate in a series of mains-borne communication trials. The purpose behind this tender was to determine whether a technical and economic future existed for such systems. Since the tender was for an experimental system, it was decided to use an architecture which was as flexible as possible. Two different systems were developed; the first used a commercially available narrowband FSK chip, whereas the second employed a wide band frequency hopping technique. The authors briefly describe the system. (0 Refs.)

INSPEC 3692863 B90057280

Title: Mains signalling

Authors: Kirk, K.

Journal: Electronics World + Wireless World

Vol: 96 Iss: 1652 p. 484-6 Date: June 1990

Abstract: The use of the mains electrical wiring for the conveying of information, either in digital form for control and computer applications or as an analogue signal for intercommunication or music transmission, seems at first glance a very sensible use of an existing resource. In this way information will be conveyed between remote corners of a home, factory or office without the cost of extra cabling and without reverting to licensed transmission methods such as radio. Indeed, with the cooperation of the relevant generating utility it may be used to return information from the customer's premises for remote meter reading, faults, service information and alarm conditions. There are, however, of course, snags, one set of which is physical and may be overcome with the judicious application of some electronics. (0 Refs.)

.INSPEC 3649188 B90041638 C90039211

Title Mains signalling-progress of a UK remote meter reading and load management system.

Authors: Billington, D.J.

Affiliation: THORN Security Ltd., Enfield, UK

Conf. Title: Sixth International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. No.317) p. 158-62 me

Publisher: IEE

London, UK

Conf. Date: 3-5 April 1990 Conf. Loc: Manchester, UK Conf. Sponsor: IEE

Abstract: The author describes the current evolution of a mains signalling spread spectrum two way communication system for remote meter reading and load management using the LV distribution network. Early development of the system was reported at the Mates 82 conference and the results of a 1000 house trial of the system was reported at Mates 87. The 1000 house trial has been followed by a contract placed by the UK Electricity Council to develop the system for volume manufacture and to manufacture 2000 sets of equipment for a pilot scheme for installation by the London Electricity Board. The author describes the stages of the development programme, the finalised specification of the equipment, detailed aspects of the system management and some of the design implications pertaining to the various national and international specifications the equipment has to meet. (3 Refs.)

INSPEC 3637407 B90041640

Title: Upwards to a reliable bidirectional communication link on the LV power supplies for utility services: field tests in Belgium

Authors: De Wilde, W.R.; Van Wassenhove, D.

Conf. Title: Sixth International Conference on Metering Apparatus and Tariffs for

Electricity Supply (Conf. Publ. No.317) p. 168-72

Publisher: IEE, London, UK

Conf. Date: 3-5 April 1990 Conf. Loc: Manchester, UK Conf. Sponsor: IEE

Treatment: Practical

Abstract: There is an increasing interest in the use of a bidirectional communication link between the electricity distribution company and the LV consumers to implement for example load management and distribution automation. installation of a local network, by use of physical links involve irresponsible costs. Using the LV power lines not only for energy distribution, but also as a communication vehicle is therefore a favourable solution. However, there are a lot of disadvantages involved. Mains signalling has the reputation of being unreliable due to the high noise levels and strange transfer characteristics which are strongly time and place dependent. The authors examine mains signalling and indicate how reliable bidirectional communication can be made by applying advanced communication and coding techniques in the frequency band of 10 kHz to 95 kHz. As an example remote meter reading, among the unlimited utility services, was used to test the communication system. (1 Refs.)

INSPEC 3637406 B90041637

Title: Experimental systems for tele-reading over the low voltage network

Authors: King, M.C.; Adame, J.; Schaub, T.; Rossi, G.; Ziglioli, F.

Conf. Title: Sixth International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. No.317) p. 154-7

Publisher: IEE, London, UK

Conf. Date: 3-5 April 1990 Conf. Loc: Manchester, UK Conf. Sponsor: IEE

Abstract: The authors describe a number of mains-borne metering systems and experiments, which have been key projects in an international research effort. This has involved collaboration with a number of academic establishments and distribution companies. The authors determine the characteristics required of software and hardware systems. The result of extensive research is a number of large networks throughout Europe. There is also a network of intelligent meters that can be configured as a portable vehicle

for measurement studies of, line time domain noise intensity, communications efficiency and many other statistical parameters. Early studies of spread spectrum experiments and differential phase shift keying (DPSK) are reported, as these assisted in defining the development of a later system. (3 Refs.)

INSPEC 3604622 B90033020 C90029887

Title: Mainsborne telecontrol: the future is now

Authors: Homer, G.

Journal: Electrical Review Vol: 223 Iss: 3 p. 23-4 Date: 7-20 Feb. 1990

Abstract: Automatic meter reading plus consumption information for the consumer is now available at an acceptable price. The supply industry sees great promise in the use of two-way mains signalling systems which offer both effective load management and instantaneous feedback of information. Here, the author describes how mainsborne signalling over the electricity distribution network, has many attractions since networks are owned by the electricity supply authority and the operation of additional services over the network does not add significantly to the running costs of the system.

INSPEC 3581346 B90024005

Title: Data transmission via domestic mains: measuring data from room to room. II

Journal: Funkschau

Iss: no.23 p. 105-7

Date: 3 Nov. 1989

Language: German

Abstract: Describes the fixing of the SF 900 reflex light barrier to the electricity meter and reproduces the complete circuit diagram of the monitor; it requires 7 ICs, 3 transistors, 8 diodes and numerous passive components, all quoted in a separate components list. Waveform diagrams and the printed board drawing are included. (0Refs.)

INSPEC 3516875 B90003763

Title: Transmission over 220 V: the power package in data transport (cable TV)

Authors: Wittmann, G.

Journal: Funkschau Iss: no.17 p. 59-60 Date: 11 Aug. 1989

Language: German

Abstract: The author's firm has developed a Hotel Pay-TV system-Argus 2000-in which all control and monitoring operations are mains-borne, suitably protected and screened by elaborate filters. The core of Argus is a PC and the so-called communications- and mains unit 'managers'. The 1st organizes the selection and transmission of programs from video recorders, feeds them to a community aerial and distributes them via concentrators. Each room TV has a built-in slave unit which responds to signals determining choice, duration and price of a program. These signals are FSK-modulated and error-corrected, and sent at 300 Baud by the mains manager via SBC's (SignaVBooster/Corrector). The basic system would serve the 'intelligent' house of the future. A schematic diagram of the complete Argus 2000 is reproduced. A 2nd one shows a bus structure model for diverse combinations of boosters and slaves, up to 258 units per system. (0 Refs.)

INSPEC 3511030 C90001436

Title: Home automation

Authors: Ryan, J.L.

Affiliation: Thorn EMI Central Res. Labs., Hayes, UK

Abstract: The impact of home automation on domestic lifestyles will be as far ranging as was that of factory automation on industry and its benefits will be available to all sectors of society. Home automation will be achieved not with the household robot but with embedded computing power and memory within dozens of pieces of domestic equipment, each of which will communicate with the user and with other equipments. Within the integrated home system the communication media will include infrared, radio, mains wires, installed twisted wires and coaxial cable, and later perhaps optical fibre. Applications will include security, lighting, heating, cooking, washing appliances, audio and video systems, energy management as well as a number of new applications such as health monitoring, home publishing etc. A large standards activity is in place by the major manufacturers of domestic equipment throughout Europe to ensure that their equipments are reliable and compatible. (10 Refs.)

INSPEC 3901162 C91040245

Title: Geadomics: the intelligent house of the future

Authors: Seyer, R.; Wempe, S.

Journal: Funkschau

Iss: no.4 p. 50-1 Date: 8 Feb. 1991

Language: German

Abstract: The European project Esprit 2431 deals with preprogrammed automated management of domestic systems such as heating, air-conditioning, kitchen and laundry machines, audio and video entertainment equipment, surveillance and protection. Mains supply, infrared, coaxial and fibre cable, and open twisted pair are used. Ecological and ergonomic aspects are considered and respected. Aiming at gradual introduction after 2000, AEG-Geadomics (part of Daimler-Benz) intend to develop a standard infrastructure for all information, communication and control requirements of future dwellings. (0 Refs.)

INSPEC 3854592 B91027256

Doc Type: Conference Paper

Title: Data communications over power circuits using direct sequence spread spectrum modulation

Authors: Saund, T.S.; Comley, V.E.; Hill, P.C.J.

Affiliation: R. Mil. Coll. of Sci., Swindon, UK

Conf. Title: IEEE International Symposium on Spread Spectrum Techniques and Applications p. 25-9

Publisher: King's College London UK

Conf. Date 24-26 Sept. 1990, Conf. Loc: London UK

Conf. Sponser: IEEE; IEE; Univ. London

Abstract: The authors consider the application of direct sequence spread spectrum modulation for data transfer over mains power circuits. Results are presented for the impedance and attenuation characteristics of typical mains power circuits, and the performance of a direct sequence transmitter and receiver operating at 488 baud is reported. The authors conclude that the establishment of local area networks using direct sequence modulation over mains power circuits is a practical proposal. (8 Refs.)

INSPEC 3846570 B91028564 C91020920

Title: Telemetering and telecontrol using the electric network.

The future begins today with Mainsborne

Authors: Homer, G.; de Snoo, J.K.

Journal: Elektrotechniek

Vol: 68 Iss: 11 p. 1001 -4 Date: Nov. 1990

Language: Dutch

Abstract: Mainsborne Telecontrol, now being manufactured by Thorn Security Ltd., is an integrated system for automatic meter reading, intelligent load control and real time feedback. The system is designed to respond to today's economic, social and political pressures for the better use of energy, reduced operating costs and greater customer satisfaction. Research and the application of modern electronics technology to solving the problems for achieving reliable two-way data communication over low voltage mains distribution network had opened up significant opportunities for supply authorities to provide a new range of services, aiding both themselves and their customers. London Electricity is now introducing tried, tested and available technology. (0 Refs.)

INSPEC 3767370 B90080610 C90068627

Title: Is control wiring losing control?

Authors: Burton, K.

Affiliation: Gratte Brothers, London, UK

Journal: Electrical Equipment p. 20-2, Sept. 1990

Abstract: A well planned power distribution will be required in any installation, but the control of this power can be achieved more efficiently, and cost effectively, if traditional methods are disregarded. The author describes a novel application of JEL's UC8000 mains signalling equipment which is used to control the electrical installation at the premises of a large retailer. (0 Refs.)

INSPEC 3767161 B90080614

Title: Future of distribution dawns in the East

Authors: Martin, D.

Journal: Electrical Review Vol: 223 Iss: 18 p. 23-4 Date: 21 Sept.-4 Oct. 1990

Abstract: The author discusses the work being carried out at Eastern Electricity's Distribution Technology Park in Colchester. The park was set up in 1989 as a five year project to put new ideas on design and equipment to the test on a real distribution network. The experimental network which consists of six underground and two overhead circuits fed by two 132/11 kV transformers supplying a range of customers from farms and heavy industry to new housing estates. Four of the circuits are fed through vacuum circuit-breakers, with the other four being fed through SF/sub 6/ breakers. The author discusses fault location including remote fault indicators using mainsborne signalling. (0 Refs.)

INSPEC 4310955 B9302-8150-030 C9302-3340H-040

Doc Type: Conference Paper

Title: Mains signalling-experience of the London Electricity 2000 unit Pilot Scheme

Authors: Billington, D.J.

Conf. Title: Seventh International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. No.367) p. 257-61

Publisher: IEE, London, UK, 1992

Conf. Date: 17-19 Nov. 1992 Conf. Loc: Glasgow, UK Conf. Sponsor: IEE

Abstract: The author describes the progress in the implementation of a mainsborne telecontrol remote meter reading and load management system to be operated as a 2000 property Pilot Scheme by London Electricity. The position regarding the development and manufacture of the constituent elements is discussed.Operation of the Pilot Scheme will be carried out by a Data Control Centre being developed under a funded contract from the Electricity Association. The facilities to be provided by the Data Control Centre to enable the Pilot Scheme to be representative of a much larger system implementation are described in detail. The timetable for the further installation and commissioning of the system is also discussed. (2 Refs.)

INSPEC 4310948 B9302-8150-023

Title: Mains communication-a practical metering system

Authors: Sheppard, T.J.

Conf. Title: Seventh International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. No.367) p. 223-7

Publisher: IEE, London, UK, 1992

Conf. Date: 17-19 Nov. 1992 Conf. Loc: Glasgow, UK Conf. Sponsor: IEE

Abstract: A practical mains communication system that works on typical LV mains networks has been the goal of the metering industry for a considerable number of years. The author describes such a system, starting with a review of the requirements of a modern metering system, both from the electricity company's and the consumers' points of view. The author examines the problems of mains communication compared to other potential communications media and shows how a narrow band, phase modulated, coherent carrier system can overcome these problems and be implemented cost effectively using modern CMOS ASICs (applications specific integrated circuits). The author shows how this communications technology is used to build a practical integrated metering system offering a full range of metering services. The results of field trials carried out using the systems are presented. (0 Refs.)

INSPEC 4310939 B9302-8150-014

Title: A common meter support system

Authors: Orchard, N.G.N.

Affiliation: Pilot Systems Ltd., London, UK

Conf. Title: Seventh International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. No.367) p. 174-9

Publisher: IEE, London, UK, 1992

Conf. Date: 17-19 Nov. 1992 Conf. Loc: Glasgow, UK Conf. Sponsor: IEE

Abstract: Until now it has not been possible to develop a support system independent of the manufacturer because there was no standard interface between the respective data. However the emergence of the EC FLAG communications protocol and the CHIRPS common HHU (hand held unit) operating system has provided a vehicle for a new standard; OMS (Open Metering System) a data standard, the next layer up from the protocol and data transfer shells. Since OMS is a data standard, it is not restricted to protocol or transfer medium. It has developed around HHU programming and reading simply because FLAG and CHIRPS are already available. OMS is an equally suitable data format for mains signalling and smart-card communication applications. The standard allows greater flexibility for the electric utility, giving it the choice for both its operational systems and the metering technology it uses. (1 Refs.)

INSPEC 4310936 B9302-8150-012

Doc Type: Conference Paper

Title: Self-testing in an electricity meter: new contribution to intelligent metering

Authors: Rozman, M.; Jeglic, A.; Jamnik, P.

Affiliation: Ljubljana Univ., Slovenia

Conf. Title: Seventh International Conference on Metering Apparatus and Tariffs for Electricity Supply (Conf. Publ. N, 1992

Conf. Date: 17-19 Nov. 1992 Conf. Loc: Glasgow, UK Conf. Sponsor: IEE

Abstract: Electronic meters enable data processing for complex tariffing purpose, mains two-way communication for remote meter reading and intelligent load control for efficient energy use. In spite of all these advantages there is still certain mistrust in using intelligent metering widely in many countries. In order to overcome these major disadvantages a self-test-autocalibration function is integrated in intelligent meters for daily examination of correct operation. (3 Refs.)

INSPEC 4201625 B9209-8150-002

Title: Meter power (electricity metering)

Authors: Dettmer, R.

Journal: IEE Review Vol: 38 Iss: 6 p. 237-40 Date: 18 June 1992

Abstract: The author discusses the problems caused by the privatisation of the UK electricity supply industry in the area of metering. The minimum requirements for changes in metering suggested by Offer (Office of Electricity Regulation) to improve demand side management, are discussed. The author then discusses communication techniques for improved metering. The author describes mains signalling and radio techniques for remote meter reading. The practical implications of using such technology and its benefits are discussed. (2 Refs.)

INSPEC 4190059 B9208-8110B-070 C9208-3340H-066

Title: Mainsborne signalling receiver and clock-two functions move closer

Authors: Dierks, E.; Kalny, F.

Affiliation: Siemens AG, Nurnberg, Germany

Journal: Elektrizitaetswirtschaft Vol: 91 Iss: 6 p. 273-4, 277-8 Date: 9 March 1992

Language: German

Abstract: Modern mainsborne signalling receivers enable plant operators to support control tasks with the aid of decentralised clocks, and equipment must perform such tasks as recognition of tariff states, load clearing, and so on, as well as classical functions of transmitting and switching. The authors introduce the new 7RR70 mainsborne signalling receiver which includes timer function and large scale integrated circuit for pre-filter, watchdog, voltage control and monitoring purposes. Classical technology is discussed and clock and timing functions are described. The transmission protocol is mentioned with reference to DIN43861. (2 Refs.)

INSPEC 4190058 B9208-8110B-069 C9208-3340H-065

Title: Mainsborne signalling control installation planning-choice of feed-in level

Authors: Paessler, E.R.

Affiliation: Siemens AG, Erlangen, Germany

Journal: Elektrizitaetswirtschaft Vol: 91 Iss: 6 p. 265-6, 269-73 Date: 9 March 1992

Language: German

Abstract: Mainsborne signalling in electrical power networks brings advantages to supply undertakings, but such systems require economic and technological consideration. Relevant matters are reviewed. In principle, control signals can be fed in at all supply voltage levels, but optimal choice depends on technical and organisational aspects. Parallel coupling into high, medium and low voltage networks at 110 kV, 10 to 30 kV, and 400 V levels respectively are considered in terms of design, problems, and costs. Signalling frequencies up to 283 Hz, 500 Hz, and 3000 Hz are quoted for high, medium, and low voltage cases. Feed methods, transmitted signal levels, operating problems, cost and other aspects are discussed. Feed-in voltage level should be decided early in the design process. (4 Refs.)

INSPEC 4190029 B9208-6240J-()O1

Doc Type: Journal Paper

Title: Borne again: mains signalling's new dawn

Authors: Rosenberger, A.

Journal: Electrical Review Vol: 225 Iss: 11 p. 32-4 Date: 29 May 1992

Abstract: The idea of using power cables for signalling purposes, thus avoiding the cost and disruption of installing dedicated wiring, has been of interest to engineers since as long ago as 1896. Five years ago, manufacturers were falling over each other to market sophisticated mains signalling systems. Few survived the stampede. Now mainsborne signalling looks set for another, more sustained. (0 Refs.)

INSPEC 4118556 B9205-0160-003

Title: Transmission of alarm and fault messages

Authors: Stief, H.; Wagner, K.

Affiliation: Zettler GmbH, Munchen, Germany

Journal: Elektro-Anzeiger Vol: 44 Iss: 11 p. 72-4, 76 Date: 15 Nov. 1991

Language: German

Abstract: The authors discuss cabling between transducers and sensors in buildings, refers to discriminators, and describes 'connection rings' for data transmission. The problem, of logging parameter trends is also examined, and 'intelligent transmission lines' for alarm transmission are described. Reference is also made to burglar detection. The use of the 220 V AC supply mains for signalling is considered, as well as radio links at 27 MHz, 40 MHz or 433 MHz. Interference from CB radio at 27 MHz is referred to. The use of the public switched telephone network for alarm telemetry is also explained, and newer systems are mentioned. (0 Refs.)

INSPEC 4069203 B9202-8110B-271 C9202-3340H-308

Title: Communication through telecontrol via the electricity network

Authors: Homer, G.E.

Journal: Elektrotechniek Vol: 69 Iss: 10 p. 839-43, Oct. 1991

Language: Dutch

Abstract: Reports on Thorn EMI's Mainsborne Telecontrol Project, indicating applications in network management and cost reduction. System structure is outlined with a brief description of the individual element involved: meters (including gas and water, as well as electricity, if desired); home unit; customer display; information processing unit; and the central controller (installed at the LV transformer substation for communication with up to 1024 home units). (0 Refs.)

Appendix 2

Listing for data entry software

```
#include <time.h>
#include <string.h>
#include <dos.h>
#include <math.h>
#include <conio.h>
#include <stdio.h>
#include <stdlib.h>
#include <stdarg.h>
#include <graphics.h>
#include <complex.h>
#include <ctype.h>

int f, d, finalx, find, listnum;
char numcab[1];
char mtch[30], k, srch, *sech, *match;
FILE *pon;
int xcabtype, ycabtype;
int phasenum, z,a,b,num,feeds,xq,yq,x,y;
int GraphDriver,GraphMode;
char buf[5],buff[30];
char phase;

double spurlen [3][100], mainlen [100];
complex spurser [100], spurpar [100], mainser [100], mainpar [100];

double startf, endf, xminus, getspurlength;
double pi= M_PI;
complex numerator, denominator, result;
complex z0_array [100];
complex z0_mainarray [100];
int getmainlen (), getphase (), numspur (), drawspur (), drawmain ();
int getspurcabledat(), getmaincabledat();
int arraytoscreen (double spurlen[3][100], double *, int,
        complex *, complex *,
        complex *, complex *);
int getspurlengths();
int cablestoscreen(), getchoice(int), findnextstring(), getnextstring(),
        numout();

int feednumber;
int getmainchoice(int),
        getmainchoice(int), getmainchoice(int);

int gctspurparam(int), getparparam(int), getserparam(int),
        getmainparam(int), getmainserparam(int), getmainparparam(int);
```

```
main()
{
int p,y;
char bu[20];
clrscr();
printf ("\n Enter number of spurs from main cable ");
p=y=0;
while ((bu[p++]=getche())!=0x0d);
feeds = atoi(&bu[y]);

/* Get the frequency range for analysis            */
p=y=0;
/**************************************************************/
/* Initialise graphics mode with auto-detection                */
int graphdriver = DETECT;
initgraph( &graphdriver, &GraphMode, "..\\bgi" );
/* Screen addressed from 0.0 top left to 640.480 bottom right    */
/* Horizontal.Vertical                                 */
/**************************************************************/

/* Main horizontal 3 phase run. */
drawmain ();

/* Vertical spurs, single or 3 phase */
/* buf contains 'A'        */
drawspur ();

/* Label the spurs*/
/* buf contains 'A'        */
numspur ();

/* Get the spur phase colours and lengths. */
/* buf contains last spur        */
getphase ();

/* Get the lengths of the main run   */
/* buf contains 'B'        */
getmainlen ();
/* At this point cable parameters are needed.           */
/* These parameters are:- R,L for series parameters.  */
/*                    G,C for parallel parameters.  */
/* The above measured between all phases and 0v/neutral   */
/* ie synchronous mode                                 */
/* these will be read from "cable.dat" if type is known     */
/* or entered from keyboard if type not known          */

getspurcabledat();

/* at this point we have,                          */
/*  Z0 for all spurs stored in   Z0_array    */
```

```
/* spur lengths stored in       spurlen [][]        */
/* main lengths stored in       mainlen []          */
/* resistance stored in  spurser[][].x              */
/* inductance stored in spurser[][].y               */
/* admittance stored in spurpar[][].x               */
/* capacitance stored in        spurpar[][].y              */
/* start frequency stored in    startf              */
/* ending frequency stored in         endf                 */

/* Also needed are the parameters between phases.   */
/* These are G and C between phases.              */
/* Termination impedences.                          */

/* buf contains last spur                           */
getmaincabledat();

getch ();           /* Pause before leaving graphics mode      */

restorecrtmode();      /* Screen back into text mode  */

/* Print arrays to screen before ending       */
arraytoscreen (spurlen, mainlen , feeds,
        spurser, spurpar,
        mainser, mainpar);

return (0);
}       /* End of main programme    */
```

```
/*************************************************************/
/* Draws the purple 3 phase 415 volt main run             */
/*************************************************************/
drawmain()
{
y=400;
x=30;

strcpy (buf, "A");
outtextxy (x,y+5,buf);
for (x=30;x<=610;x++)
      {
      putpixel(x,y,5);          /* Page 75 for colours      */
      }
return(0);
}


/*************************************************************/
/* Draws the spurs, 1 or 3 phase coming off the main 3 phase run*/
/*************************************************************/
drawspur()
{
int drawfeed;
xminus = (x-50)/feeds;  /* xminus = number to subtract from x for drawing */
for (drawfeed=(feeds-1);drawfeed>=0;drawfeed--)
      {
      for (y=400;y>=150;y--)
            {
            putpixel(x,y,7);   /* Page 75 for colours  */
            }
      x=x-xminus;
      }
finalx=x;
return(0);
}
```

```
/*************************************************************************/
/* Assign letters to each of the spurs, starting with 'B' up to B+feeds    */
/*************************************************************************/
numspur ()
{
/* xq & yq are values for the positioning of questions on the screen     */
/* x & y are used for drawing and for text on the drawing              */
xq=0;
yq=60;
y=415;
x=x+xminus;
for (x=x;x<=611;x=x+xminus)
      {
      buf[0] = buf[0]++;        /* next capital letter     */
      outtextxy (x,y+5,buf);  /* Put letter on screen  */
      }
return(0);
}

/*************************************************************************/
/* Phase array 2 dimension, spur length in corresponding position*/
/* Floating point array                                  */
/*            R  0ABC00F0                          */
/* Phase     B  00B0000G-----Length of spur                   */
/*            Y  00B0DE00                                  */
/*             |______| Number of spurs                    */
/*************************************************************************/
getphase ()
{
double length;
int feednumber;
x=finalx+xminus;
buf[0] = 'A';        /* Set buf[] to beginning */

for (feednumber=0 ;feednumber<=(feeds-1);feednumber++)
      {
      settextstyle (0,0,0);       /* Horizontal text*/
      setcolor (15);               /* White text              */
      outtextxy (xq,yq,"Enter the phase colour of the spur marked");
      setcolor (0);                /* Black text              */
      outtextxy (xq,yq+20,buf);
      setcolor (15);               /* White text              */
      buf[0]++;
      outtextxy (xq,yq+20,buf);
      phase = toupper (getch());
      switch (phase)
            {
            case 'R':      /* Red phase        */
                  {
```

```
            length = getspurlengths();
            spurlen[0][feednumber]=length;  /*              */
            spurlen[1][feednumber]=NULL;   /* Fill array  */
            spurlen[2][feednumber]=NULL;   /*              */
            for (y=400;y>=150;y--)
                {
                putpixel(x,y,4);    /* Red spur */
                }
            break;
            }
        case 'B':    /* Blue phase      */
            {
            length = getspurlengths();
            spurlen[0][feednumber]=NULL;
            spurlen[1][feednumber]=length;     /* Fill array */
            spurlen[2][feednumber]=NULL;
            for (y=400;y>=150;y--)
                {
                putpixel(x,y,3);    /* Blue spur       */
                }
            break;
            }
        case 'Y':    /* Yellow phase   */
            {
            length = getspurlengths();
            spurlen[0][feednumber]=NULL;
            spurlen[1][feednumber]=NULL;     /* Fill array */
            spurlen[2][feednumber]=length;
            for (y=400;y>=150;y--)
                {
                putpixel(x,y,14);  /* Yellow spur     */
                }
            break;
            }
        default :    /* All phases on spur    */
            {
            length = getspurlengths();
            spurlen[0][feednumber]=length;
            spurlen[1][feednumber]=length;     /* Fill array */
            spurlen[2][feednumber]=length;

            for (y=400;y>=150;y--)
                {
                putpixel(x,y,5);    /* Purple spur     */
                }
            break;
            }
        }    /* end switch */
    x=x+xminus;      /* Do next spur   */
    }
```

```
setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the phase colour of the spur marked");
outtextxy (xq,yq+20,buf);

return(0);
}

/*************************************************************/
/* Get the lengths of the spurs starting at far end          */
/*************************************************************/
getspurlengths()
{
double length;
y=150;
a=0;
settextstyle (0,0,1);      /* Horizontal text*/
setcolor (0);
outtextxy (xq,yq,"Enter the phase colour of the spur marked");
setcolor (15);
outtextxy (xq,yq,"Enter the length of the spur marked");
while ((buff[a++]=getch())!=0x0d);

buff[--a]=NULL;
settextstyle (0,1,1);      /* Vertical text    */
outtextxy (x,y,buff);
length = atof(&buff[z]);

settextstyle (0,0,1);      /* Horizontal text*/
setcolor (0);
outtextxy (xq,yq,"Enter the length of the spur marked");
outtextxy (xq,yq+20,buf);
return (length);
}


/*********************************************************************/
/* Get the individual lengths of the main run between each of the spurs */
/*********************************************************************/
getmainlen()
{
double length;
x=70;
y=405;
buf[0]='A';       /* Set buf[0] to 'A' */
setcolor (15);
outtextxy (xq,yq,"Enter the length between the points marked");

for (b=0;b<=feeds-1;b++)
```

```
        {
        buf[0]--;
        setcolor (0);
        outtextxy (xq,yq+20,buf);
        buf[0]++;
        outtextxy (xq+40,yq+20,buf);

        setcolor (15);
        outtextxy (xq,yq+20,buf);
        outtextxy (xq+10,yq+20,"and");

        buf[0]++;
        outtextxy (xq+40,yq+20,buf);
        a=0;
        while ((buff[a++]=getch())!=0x0d);
        buff[--a]=NULL;
        outtextxy (x,y,buff);
        length = atof(&buff[z]);
        mainlen [b]= length;
        x=x+xminus;
        }
 setcolor (0);
 outtextxy (xq,yq,"Enter the length between the points marked");
 buf[0]--;
 setcolor (0);
 outtextxy (xq,yq+20,buf);
 buf[0]++;
 outtextxy (xq+40,yq+20,buf);
 outtextxy (xq+10,yq+20,"and");
 return(0);
 }
/*******************************************************/
/* Get the cable data for the spurs                    */
/*******************************************************/

getspurcabledat()
{
int ctype, feednumber;

buf[0]='A';

for (feednumber=0;feednumber<=(feeds-1);feednumber++)
      {
      settextstyle (0,0,1);     /* Horizontal text*/
      setcolor (15);            /* White text          */
      outtextxy (xq,yq,"Enter the type of cable from list for spur marked");
      setcolor (0);             /* Black text          */
      outtextxy (xq,yq+20,buf);
      setcolor (15);            /* White text          */
      buf[0]++;
```

```
	outtextxy (xq,yq+20,buf);
	outtextxy (xq+20,yq+20,", Enter 'N' for none.");

	/* In here we need to print the cables from 'cable.dat' */

	setcolor (15);
	cablestoscreen();
	getchoice(feednumber);

	setcolor (0);		/* Black to erase the question text  */
	cablestoscreen();

	outtextxy (xq,yq,"Enter the type of cable from list for spur marked");
	outtextxy (xq,yq+20,buf);
	outtextxy (xq+20,yq+20,", Enter 'N' for none.");

	}
return(0);
}

/****************************************************************/
/****************************************************************/
cablestoscreen ()
{
xcabtype = 10;
ycabtype = 90;
strcpy (numcab,"0");
pon = fopen("cable.dat","rb");
listnum = 0;
while (1)
	{
	find = findnextstring();
	if (find == 1)
		{
		getnextstring();
		listnum++;
		numcab[0]++;
		ycabtype = ycabtype+10;
		numout();
		}
	else break;
	}
fclose (pon);
return(0);
}
```

```
/********************************/
findnextstring()
{
int c;
c=0;
do
	{
	srch = fgetc (pon);
	if (c++ == 40)
		{
		return 0;
		}
	}
while (srch != '/');
return 1;
}
/********************************/
getnextstring ()
{
d=1;
mtch[0]=fgetc(pon);
do
	{
	mtch[d]=fgetc(pon);
	d++;
	}
while (mtch[d-1]!='_');
return (0);
}

/********************************/
numout ()
{
int e;
mtch [d-1] = NULL;
outtextxy (xcabtype+20,ycabtype, mtch);
numcab[1] = NULL;
outtextxy (xcabtype,ycabtype,numcab);
return(0);
}
/********************************/
```

```
getchoice(int feednumber)
{
int num;
pon = fopen("cable.dat","rb");
setcolor (0);
outtextxy (300,100," Invalid choice \n");
num = toupper(getch());
num = num - 0x31;

if (num+0x31=='N')     /* sort out parameters for cables not on file      */
        {
        getserparam(feednumber);
        getparparam(feednumber);
        }

else if (num< 0 || num > listnum-1)
        {
        setcolor (15);
        outtextxy (300,100," Invalid choice \n");
        return(0);
        }
else
        {
        for (f=0;f<=num;f++)
                {
                findnextstring();
                }
        getnextstring();
        getspurparam(feednumber);
        }
fclose (pon);
return (0);
}
/*********************/
/*********************/
getspurparam(int feednumber)
{
int e;
double rea, ima;
d=1;
mtch[0]=fgetc(pon);
do
        {
        mtch[d]=fgetc(pon);
        d++;
        }
while (mtch[d-1]!='_');
mtch[d-1]=NULL;
rea = atof(mtch);
d=1;
```

```
mtch[0]=fgetc(pon);
do
	{
	mtch[d]=fgetc(pon);
	d++;
	}
while (mtch[d-1]!='_');
mtch[d-1]=NULL;
ima = atof(mtch);
spurser [feednumber] = complex(rea,ima);

d=1;
mtch[0]=fgetc(pon);
do
	{
	mtch[d]=fgetc(pon);
	d++;
	}
while (mtch[d-1]!='_');
mtch[d-1]=NULL;
rea = atof(mtch);
d=1;
mtch[0]=fgetc(pon);
do
	{
	mtch[d]=fgetc(pon);
	d++;
	}
while (mtch[d-1]!=0x0d);
mtch[d-1]=NULL;
ima = atof(mtch);
spurpar [feednumber] = complex (rea,ima);
return(0);
}

/****************************************************************/
/* Get the series resistance and inductance of the spurs       */
/****************************************************************/
getserparam(int feednumber)
{
double rea, ima;
settextstyle (0,0,1);     /* Horizontal text*/
setcolor (0);             /* Black text          */
outtextxy (xq+20,yq+20,", Enter 'N' for none.");
outtextxy (xq,yq,"Enter the type of cable from list for spur marked");
setcolor (15);            /* White text          */
outtextxy (xq,yq,"Enter the series resistance of the spur marked");
outtextxy (xq,yq+20,buf);
a=0;
while ((buff[a++]= getch())!= 0x0d);
```

```
buff[--a]=NULL;
rea = atof(&buff[z]);

setcolor (0);        /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the series resistance of the spur marked");
outtextxy (xq,yq+20,buf);


settextstyle (0,0,1);     /* Horizontal text*/
setcolor (15);            /* White text              */
outtextxy (xq,yq,"Enter the series inductance of the spur marked");
outtextxy (xq,yq+20,buf);
a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;
ima = atof(&buff[z]);
spurser [feednumber] = complex (rea,ima);
setcolor (0);        /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the series inductance of the spur marked");
outtextxy (xq,yq+20,buf);
return(0);
}

getparparam(int feednumber)
{
double rea, ima;
settextstyle (0,0,1);     /* Horizontal text*/
setcolor (15);            /* White text              */
outtextxy (xq,yq,"Enter the admittance of the spur marked");
outtextxy (xq,yq+20,buf);
a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;

rea = atof(&buff[z]);

setcolor (0);        /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the admittance of the spur marked");
outtextxy (xq,yq+20,buf);

settextstyle (0,0,1);     /* Horizontal text*/
setcolor (15);            /* White text              */
outtextxy (xq,yq,"Enter the capacitance of the spur marked");
outtextxy (xq,yq+20,buf);
a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;

ima = atof(&buff[z]);
spurpar [feednumber] = complex (rea,ima);
```

```
setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the capacitance of the spur marked");
outtextxy (xq,yq+20,buf);
return(0);
}

/************************************************************/
getmaincabledat()
{
int ctype, feednumber;
x=611;
buf[0]='A';
for (feednumber=0;feednumber<=feeds-1;feednumber++)
	{
	buf[0]--;
	setcolor (15);
	outtextxy (xq,yq,"Enter the cable type between the points marked");
	setcolor (0);
	outtextxy (xq,yq+20,buf);
	buf[0]++;
	outtextxy (xq+40,yq+20,buf);

	setcolor (15);
	outtextxy (xq,yq+20,buf);
	outtextxy (xq+10,yq+20,"and");

	buf[0]++;
	outtextxy (xq+40,yq+20,buf);
	a=0;
	setcolor (15);

	cablestoscreen();
	getmainchoice(feednumber); /*  get main choice       */

	setcolor (0);       /* Black to erase the question text  */
	cablestoscreen();

	setcolor (0);
	outtextxy (xq,yq,"Enter the cable type between the points marked");
	buf[0]--;
	setcolor (0);
	outtextxy (xq,yq+20,buf);
	buf[0]++;
	outtextxy (xq+40,yq+20,buf);
	outtextxy (xq+10,yq+20,"and");
	}
return(0);
}

/**************************************************************/
```

```
getmainchoice(int feednumber)
{
int num;
pon = fopen("cable.dat","rb");
setcolor (0);
outtextxy (300,100," Invalid choice \n");
num = toupper(getch());
num = num - 0x31;

if (num+0x31=='N')      /* sort out parameters for cables not on file        */
        {
        getmainserparam(feednumber);
        getmainparparam(feednumber);
        }

else if (num< 0 || num > listnum-1)
        {
        setcolor (15);
        outtextxy (300,100," Invalid choice \n");
        return(0);
        }
else
        {
        for (f=0;f<=num;f++)
                {
                findnextstring();
                }
        getnextstring();
        getmainparam(feednumber);
        }
fclose (pon);
return(0);
}

/************************************************************/
getmainparam(int feednumber)
{
double rea, ima;
d=1;
mtch[0]=fgetc(pon);
do
        {
        mtch[d]=fgetc(pon);
        d++;
        }
while (mtch[d-1]!='_');
mtch[d-1]=NULL;

rea = atof(mtch);
d=1;
```

```
mtch[0]=fgetc(pon);
do
        {
        mtch[d]=fgetc(pon);
        d++;
        }
while (mtch[d-1]!='_');
mtch[d-1]=NULL;
ima = atof(mtch);
mainser [feednumber] = complex (rea,ima);
d=1;
mtch[0]=fgetc(pon);
do
        {
        mtch[d]=fgetc(pon);
        d++;
        }
while (mtch[d-1]!='_');
mtch[d-1]=NULL;

rea = atof(mtch);
d=1;
mtch[0]=fgetc(pon);
do
        {
        mtch[d]=fgetc(pon);
        d++;
        }
while (mtch[d-1]!=0x0d);
mtch[d-1]=NULL;

ima = atof(mtch);
mainpar [feednumber] = complex (rea,ima);
return(0);
}
/*****************************************************************/
/* Get the series resistance and inductance of the main lengths      */
/*****************************************************************/
getmainserparam(int feednumber)
{
double rea, ima;
x=611;
buf[0]--;
settextstyle (0,0,1);        /* Horizontal text*/
setcolor (0);                /* Black text          */
outtextxy (xq+20,yq+20,", Enter 'N' for none.");
outtextxy (xq,yq,"Enter the cable type between the points marked");
setcolor (15);               /* White text          */
outtextxy (xq,yq,"Enter the resistance of the main cable between");
buf[0]--;
```

```
setcolor (0);
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");
        setcolor (15);
        outtextxy (xq,yq+20,buf);
        outtextxy (xq+10,yq+20,"and");

        buf[0]++;
        outtextxy (xq+40,yq+20,buf);
a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;

rea = atof(&buff[z]);

setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the resistance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");


settextstyle (0,0,1);     /* Horizontal text*/
setcolor (15);            /* White text              */
outtextxy (xq,yq,"Enter the inductance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");

a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;
ima = atof(&buff[z]);
mainser [feednumber] = complex (rea,ima);
setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the inductance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");
return(0);
}
```

```
getmainparparam(int feednumber)
{
double rea, ima;
x=611;
settextstyle (0,0,1);       /* Horizontal text*/
setcolor (15);              /* White text          */
outtextxy (xq,yq,"Enter the admittance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");

a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;

rea = atof(&buff[z]);

setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the admittance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");

settextstyle (0,0,1);       /* Horizontal text*/
setcolor (15);              /* White text          */
outtextxy (xq,yq,"Enter the capacitance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");
a=0;
while ((buff[a++]= getch())!= 0x0d);
buff[--a]=NULL;

ima = atof(&buff[z]);
mainpar [feednumber] = complex (rea,ima);
setcolor (0);       /* Black to erase the question text  */
outtextxy (xq,yq,"Enter the capacitance of the main cable between");
buf[0]--;
outtextxy (xq,yq+20,buf);
buf[0]++;
outtextxy (xq+40,yq+20,buf);
outtextxy (xq+10,yq+20,"and");
return(0);
}
```

Appendix 3

Listing for data calculation software

```
/* Main programme that calls functions in the other three units     */
#include <stdio.h>;
#include <conio.h>;
#include <math.h>;
#include <complex.h>;

int print_matrix(complex[3][3]);
double resistance(double, char, double, char, double, double, double);
double capacitance( double, double, double);
double conductance ( double, double, double);
double core_capacitance ( double, double, double);
double cre_she_3_capacitance(double, double, double, double);
double cre_cre_3_capacitance(double, double, double);
double cre_she_3_conductance(double, double, double, double);
double cre_cre_3_conductance(double, double, double);
double core_conductance ( double, double, double);
struct complex Zin_single (int a, double frequency,
            double spur_param[4][50], double spurlength);
struct complex Zin_three ( int a, double frequency, double, complex Zterm[3][3],
                double main_param[6][50], complex Zin_3[50][3][3]);

struct complex Vin_three( int a, double frequency, double,
            complex Zterm[3][3], complex Zsrce[3][3],
            double main_param[6][50], complex Vin[3], complex Vmat[3]);

getdata(char[50], char[50], char[50], char[50],
double[3][50], double[50], double[50], double[50],
double[50], char[50], double[50], double[50], double[50], double[50],
double[50], double[50], double[50], double[50]);
```

```
main()
{
FILE *results;
char main_core_type[50];
double main_core_strand[50], main_screen_strand[50];
double spur_core_strand[50], spur_screen_strand[50]; /* move this later*/
int red=0, blue, yellow=2, phasenum;
int feeds, a, x, y;
double res, cap, ind, frequency, spur_conductance[50], main_conductance[50];
complex Zin[3][50];
complex Ztermmat[3][50];
char spur_core_material[50], spur_shield_material[50];
char main_shield_material[50], main_core_material[50];
double spurlength [3][50], mainlength [50], spur_core_diameter[50];
double spur_shield_diameter[50], spur_permeability[50];
double main_core_diameter[50], main_shield_diameter[50];
double main_permeability[50], main_core_seperation[50];
double spur_param[4][50];
double main_param[6][50];
complex Zin_3[50][3][3];
complex Zsource_3[50][3][3];
complex Zsrce[50][3][3];
complex Zterm[50][3][3];
complex Vin[50][3];
complex Vmat[50][3];

complex gain[3][3];
double magnitude;

feeds = getdata(spur_core_material, spur_shield_material,main_shield_material,
main_core_material, spurlength, mainlength, spur_core_diameter,
spur_shield_diameter, spur_permeability,
main_core_type, main_core_diameter,
main_shield_diameter, main_permeability, main_core_seperation,
spur_core_strand, spur_screen_strand, main_core_strand, main_screen_strand);

/* define source impedance to be 50 ohms at sending end initially at       */
/* present source is 50 for each phase because Vin is on all phases        */

for (x=0; x<=2; x++)
    {
    for (y=0; y<=2; y++)
        {
        Zsrce[0][x][y] = pow10(10);
        }
    Zsrce[0][x][x] = (complex)50;
    Vin[0][x] = .4471;//.447;      /* Puts 0 dBm into 50 ohms */
    }
    Zsrce[0][0][2] = pow10(10);
    Vin[0][2] = 0;//.447;    /* Puts 0 dBm into 50 ohms */
```

```
        Zsrce[0][0][1] = pow10(10);
        Vin[0][1] = 0;//.447;    /* Puts 0 dBm into 50 ohms */

//calculate c, l, g for all spurs and main feeds
clrscr();
results = fopen ("results.txt","wb");
for (a=0; a<=feeds-1; a++)
        {
// to be removed after
spur_conductance[a] = pow10(-16);
main_conductance[a] = pow10(-16);

// Single capacitance
spur_param[1][a] = capacitance(spur_core_diameter[a],
        spur_shield_diameter[a], spur_permeability[a]);

// Single inductance
spur_param[2][a] = 4*M_PI*pow10(-7)*8.855*pow10(-12)*spur_permeability[a]/
spur_param[1][a];

// Single conductance
spur_param[3][a] = conductance (spur_core_diameter[a],
        spur_shield_diameter[a], spur_conductance[a]);
clrscr();

// Core - Core capacitance (3 phase)
main_param[2][a] = cre_cre_3_capacitance(main_core_diameter[a],
                                main_core_seperation[a], main_permeability[a]);

// Core - Shield capacitance (3 phase)
main_param[1][a] = cre_she_3_capacitance(main_core_diameter[a],
main_shield_diameter[a],
                                main_param[2][a], main_permeability[a]);

// Inductance
main_param[3][a] = 4*M_PI*pow10(-7)*8.855*pow10(-12)*main_permeability[a]/
main_param[1][a];
main_param[4][a] = 2*M_PI*pow10(-7)*8.855*pow10(-12)*main_permeability[a]/
main_param[2][a];

// Conductance
main_param[6][a] = cre_cre_3_conductance (main_core_diameter[a],
                                main_shield_diameter[a], main_conductance[a]);

main_param[5][a] = cre_she_3_conductance (main_core_diameter[a],
main_shield_diameter[a],
                        main_param[6][a], main_conductance[a]);
        }
// Now have R,C,L,G, for single phase in spur_param [1][a] to [4][a]
// And R,Cc,Cs,Lc,Ls,Gc,Gs, for three phase in main_param[1][a] to [6][a]
```

```
// 1 Meg to 10 Meg, step 100k
for (frequency=pow10(6);frequency<=pow10(7);frequency=frequency+pow10(5))
// phase order in datafile is red, blue, yellow
        {
//      eachspur starting at sending end
        for (a=0; a<=feeds-1; a++)
                {
                /* Need stranded info    */
                spur_param[0][a] = resistance(frequency,
                        spur_core_material[a],
                        spur_core_diameter[a],
                        spur_shield_material[a],
                        spur_shield_diameter[a],
                        spur_core_strand[a], spur_screen_strand[a]);

                main_param[0][a]= resistance(frequency,
                        main_core_material[a],
                        main_core_diameter[a],
                        main_shield_material[a],
                        main_shield_diameter[a],
                        main_core_strand[a], main_screen_strand[a]);

                for (phasenum = red; phasenum <= yellow; phasenum++)
                        {
                        if (spurlength[phasenum][a] ==0)
                                { Zin[phasenum][a]=pow10(10);}
                        else
                                {
                Zin[phasenum][a] = Zin_single
                        ( a, frequency, spur_param, spurlength[phasenum][a]);
                                }/* end 'spur or not' */
                        }/* end of 3 phases */
/* Zsrce is temporary impedance looking back to source                  */
/* Zsource_3 impedance looking to source without spur at that joint     */
/*************************************************************************/
                Zin_three
                        ( a, frequency, mainlength[a],
                                Zsrce[a], main_param, Zsource_3);
                for (x=0; x<=2; x++)
                        {
                        for (y=0; y<=2; y++)
                                {
                                Zsrce[a+1][x][y] = Zsource_3[a][x][y];
                                }
if ((a<=feeds-2)&&(Zin[x][a]!= (complex)pow10(10))) Zsrce[a+1][x][x]
                                = Zsource_3[a][x][x]*Zin[x][a]/
                                (Zsource_3[a][x][x]+Zin[x][a]);
                        }
// This gives us a series of '3 X feeds' arrays with
```

```
// '10^10' if there is no spur and 'Z' if there is a spur
            }/* end of each spur */
/* From far end to near end */
//need to define initial matrix for termination
      for (x=0; x<=2; x++)
            {
            for (y=0; y<=2; y++)
                  {
                  Zterm[feeds][x][y] = pow10(10);
                  }
            if (Zin[x][feeds-1]!=(complex)pow10(10))
            Zterm[feeds][x][x] = Zin[x][feeds-1];
            }
/*************************************************************************/
/*    Calc main Z looking into network from sending direction           */
/*************************************************************************/
      for (a=feeds-1; a>=0; a--)
            {
            Zin_three
                  ( a, frequency, mainlength[a],
                        Zterm[a+1], main_param, Zin_3);
/* comes back with Zin_3[a] as a 3X3 matrix    */
            for (x=0; x<=2; x++)
                  {
                  for (y=0; y<=2; y++)
                        {
                        Zterm[a][x][y] = Zin_3[a][x][y];
                        }
      if ((a>=1) && (Zin[x][a-1]!= (complex)pow10(10)))
            Zterm[a][x][x] = Zin_3[a][x][x]*Zin[x][a-1]/
                                    (Zin_3[a][x][x]+Zin[x][a-1]);
                  }


            }
/* (Zin_3[0][x][x]) and all spur joints up to Zin_3[feeds-1][x][x] */
      for (a=0; a<=feeds-1; a++)
            {
            Vin_three( a, frequency, mainlength[a],
                  Zterm[a+1], Zsrcc[a], main_param, Vin[a], Vmat[a]);
            for (x=0; x<=2; x++)
                  {
                  for (y=0; y<=2; y++)
                        {
                        gain[x][y] = Vmat[a][x];
                        }
                  }
```

```
/* Got to make Vin[a] = Vmat[a-1] for next series
        magnitude = sqrt(real(gain[0][0])*real(gain[0][0])+
                    imag(gain[0][0])*imag(gain[0][0]));

                    magnitude = 20*log10(magnitude);
               fprintf (results,"%e        ",magnitude, "wb");

        magnitude = sqrt(real(gain[1][1])*real(gain[1][1])+
                    imag(gain[1][1])*imag(gain[1][1]));

                    magnitude = 20*log10(magnitude);
               fprintf (results,"%e        ", magnitude, "wb");

        magnitude = sqrt(real(gain[2][2])*real(gain[2][2])+
                    imag(gain[2][2])*imag(gain[2][2]));
                    magnitude = 20*log10(magnitude);
               fprintf (results,"%e        ",magnitude, "wb");

               }
        fprintf (results,"\n", "wb");
        }/* end of that frequency */
return(0);
}
```

```
/* Contains single phase functions and                 */
/* cable parameter calculation functions    */
#include "complex.h"
#include <math.h>
#include <dos.h>
#include <stdio.h>
#include <stdlib.h>
#include <ctype.h>
#include <conio.h>
/* Now we need to do some calculations.                 */

int ap, spurlen, phasenum, capmul;
FILE *output;

/*******************************************************************/
complex Zin_single(int a, double frequency,
                double spur_param[4][50], double spurlength)
{
int b, matched;
struct complex z0calc(complex , complex , double );
struct complex gammacalc(complex , complex , double);
complex seriesdata, paralleldata, series;
complex z0, z0sq;
complex gamma, gammasq;
complex gammalen;
complex Z, calcZ(complex , complex , complex );
complex zr, zterm, zspur;
zterm = 50;
seriesdata = complex (spur_param[0][a], 2*M_PI*frequency*spur_param[2][a]);
paralleldata = complex (spur_param[3][a], 2*M_PI*frequency*spur_param[1][a]);
z0sq = seriesdata / paralleldata;
z0 = sqrt(z0sq);
gammasq = seriesdata * paralleldata;
gamma = sqrt(gammasq);
gammalen = gamma * spurlength;
Z = calcZ (zterm, gammalen, z0);
return(Z);
}

/*******************************************************************/
```

```
struct complex calcZ (struct complex zr,
                    struct complex gammalen, struct complex z0)
{
struct complex exgam, mid1, mid2, mid3, mid4, mid5, mid6, mid7, Z;
// I think I need to go exponential
mid1 = zr * cosh(gammalen);
mid2 = z0 * sinh(gammalen);
mid3 = z0 * cosh(gammalen);
mid4 = zr * sinh(gammalen);
mid5 = mid1 + mid2;
mid6 = mid3 + mid4;
mid7 = mid5 / mid6;
Z = (z0 * mid7);
return Z;
}

/*****************************************************************/
double resistance(double frequency, char core_material, double core_dia
            , char screen_material, double screen_dia
            , double core_strand, double screen_strand)
{
double rocu = 1.673 * pow10(-8);
double roal = 2.655 * pow10(-8);
double ro, delta, ratio;
double res, coreR, screenR;
double corerad = core_dia * pow10(-3)/2; /* mm into metres      */
double screenrad = screen_dia * pow10(-3)/2;
double corearea, screenarea, rad;
core_strand = 0;
screen_strand = 0;
ratio = 1;
if (toupper(core_material) == 'C')
      ro = rocu;
else ro = roal;
delta = sqrt(ro/(M_PI*M_PI*4*pow10(-7)*frequency));
if (core_strand != 0)
      {
      rad = core_strand;
      ratio = ((rad*rad*acos((rad-delta)/rad))-(rad-delta)*sqrt(rad*rad-(rad-delta)*(rad-
delta)))/(2*rad*delta);
      }
corearea=M_PI*(corerad*corerad-((corerad-delta)*(corerad-delta)))*ratio;
coreR=ro/corearea ;

ratio = 1;
if (toupper(screen_material) == 'C')
      ro = rocu;
else ro = roal;
delta = sqrt(ro/(M_PI*M_PI*4*pow10(-7)*frequency));
if (screen_strand != 0)
```

```
	{
	rad = screen_strand;
	ratio = ((rad*rad*acos((rad-delta)/rad))-(rad-delta)*sqrt(rad*rad-(rad-delta)*(rad-
delta)))/(2*rad*delta);
	}

screenarea=(M_PI*((screenrad+delta)*(screenrad+delta))-
M_PI*screenrad*screenrad)*ratio;
screenR=ro/screenarea ;

res=(coreR+screenR);
return (res);
}

/*****************************************************************/
double capacitance( double core , double shield , double perm)
{
double cap;
cap = 2 * M_PI * 8.855 * pow10(-12) * perm / log(shield/core);
return(cap);
}

/*****************************************************************/
double conductance ( double core, double shield, double conductivity)
{
double cond;
cond = M_PI * conductivity / log((shield)/core);
return(cond);
}

/
*******************************************************************/
double cre_cre_3_capacitance(double core, double shield, double perm)
{
double cap;
// 2nd order equation 52 in TR3.PM5
cap = perm * 8.855*pow10(-12) *(2.03*pow(2,(core/shield))-4.54*(core/shield)+1.5);
return(cap);
}

/*****************************************************************/
double cre_she_3_capacitance(double core, double shield,
			double cre_cre, double perm)
{
double cap;
// 2nd order equation 56 in TR4.PM5 - 2nd order equation 52 in TR3.PM5
cap =(perm*8.855*pow10(-12)*(149.8*pow(2,(core/shield))-37.44*(core/shield)+5.44))-
cre_cre;
return(cap);
}
```

```
double cre_cre_3_conductance(double core,
                             double shield, double conductivity)
{
double cond;
// 2nd order equation 52 in TR3.PM5
cond = conductivity * (2.03*pow(2,(core/shield))-4.54*(core/shield)+1.5);
return(cond);
}

/*****************************************************************/
double cre_she_3_conductance(double core, double shield,
                             double cre_cre, double conductivity)
{
double cond;
// 2nd order equation 56 in TR4.PM5 - 2nd order equation 52 in TR3.PM5
cond= (conductivity * (149.8 *pow(2,(core/shield))- 37.44 *(core/shield)+5.44))-cre_cre;
return(cond);
}
```

```
/* To go with clc.cpp, clcthree.cpp, clcsingl.cpp, clcnoinv.cpp*/
// This programme implements the equations given in reference 46
/* This file contains the functions for        */
/* crunching the three phase equations      */
#include <math.h>
#include <complex.h>
#include <stdio.h>
#include <iostream.h>
#include <complex.h>
#include <stdlib.h>
#include <conio.h>

// Define the functions used
print_matrix(complex [3][3]);
complex determinant(complex a[3][3]);
complex root_mat(complex root[3][3]);
complex mult_mat(complex a[3][3], complex b[3][3], complex resadd[3][3]);
complex inverse (complex a[3][3], complex b[3][3]);
complex sub_mat(complex a[3][3], complex b[3][3], complex ressub[3][3]);
complex add_mat(complex a[3][3], complex b[3][3], complex resadd[3][3]);
complex pre_inv_mul(complex in1[3][3], complex in2[3][3], complex out[3][3]);
complex post_inv_mul(complex in1[3][3], complex in2[3][3], complex out[3][3]);
complex Zmatrix(complex y0[3][3], complex  ro[3][3], complex  gamalen[3][3], complex
Zmat[3][3]);
complex Vmatrix(complex [3][3], complex[3] , complex[3][3] ,
            complex[3][3] , complex[3][3] , complex[3] );

/
****************************************************************************/
/***************************************************************************/
// Called by zin_three to calculate impedance of any length of
// three phase cable with any termination matrix, Implements equation 29
complex Zmatrix(complex invz0mat[3][3],
            complex ro[3][3], complex gamalen[3][3], complex zma[3][3])
{
complex Iplusegamroegam[3][3], Iminusegamroegam[3][3];
complex identity[3][3], almost[3][3];
complex expgamalen[3][3], egamro[3][3], egamroegam[3][3];

int x, y;
for (x=0;x<=2;x++)
    {
    for (y=0;y<=2;y++)
        {
        identity[x][y] = 0;
        expgamalen[x][y] = exp(-gamalen[x][y]);
        }
    identity [x][x] = 1;
    }
mult_mat(expgamalen, ro, egamro);
```

```
mult_mat(egamro, expgamalen, egamroegam);
add_mat(identity, egamroegam, Iplusegamroegam);
sub_mat(identity, egamroegam, Iminusegamroegam);
post_inv_mul(Iplusegamroegam, Iminusegamroegam, almost);
post_inv_mul(almost, invz0mat, zma);
return(0);
}
/*****************************************************************/
// Reflection coefficient at the load, 3x3 matrix
complex refcoef( complex zl[3][3], complex y0[3][3], complex ro[3][3])
{
int x,y;
complex num[3][3], c[3][3];
complex identity[3][3];
complex denom[3][3];

for (x=0;x<=2;x++)
	{
	for (y=0;y<=2;y++)
		{
		identity[x][y] = 0;
		}
	identity [x][x] = 1;
	}
mult_mat(zl, y0, c);
sub_mat(c, identity, num);
add_mat(c, identity, denom);
pre_inv_mul(denom, num, ro);
return(0);
}
/*****************************************************************/
// Multiply 2, 3x3 matrices
complex mult_mat(complex a[3][3], complex b[3][3], complex resmul[3][3])
{
int x, y;
for (x=0;x<=2;x++)
	{
	for (y=0;y<=2;y++)
		{
	resmul[x][y] = a[x][0]*b[0][y] + a[x][1]*b[1][y] + a[x][2]*b[2][y];
		}
	}
return (0);
}

/*****************************************************************/
// Add 2, 3x3 matrices
complex add_mat(complex a[3][3], complex b[3][3], complex resadd[3][3])
{
int x, y;
```

```
for (x=0;x<=2;x++)
      {
      for (y=0;y<=2;y++)
            {
      resadd[x][y] = a[x][y] + b[x][y];
            }
      }
return (0);
}

/*******************************************************************/
// Subtract 2, 3x3 matrices
complex sub_mat(complex a[3][3], complex b[3][3], complex ressub[3][3])
{
int x, y;
for (x=0;x<=2;x++)
      {
      for (y=0;y<=2;y++)
            {
      ressub[x][y] = a[x][y] - b[x][y];
            }
      }
return (0);
}

/*******************************************************************/
// Square root of a 3x3 matrix, only valid if there is one value in all
// locations on the leading diagonal and one value elsewhere in the matrix.
// Of the four possible roots the solution taken has shown itself valid
// for three phase lines.
complex root_matrix(complex A, complex B, complex rootis[3][3])
{
complex a, b;
b = (sqrt(A+2*B)+sqrt(A-B))/3;
a = (B-b*b)/(2*b);
rootis[0][0] = rootis[1][1] = rootis[2][2] = a;
rootis[0][1] = rootis[0][2] = rootis[1][0] =
rootis[1][2] = rootis[2][0] = rootis[2][1] = b;
return(0);
}
/
*********************************************************************/
// Used to print a 3x3 matrix to the screen, used for debugging only
print_matrix (complex ndat [3][3])
{
printf ("\n");
printf (" %.3e %+.3ej ",ndat [0][0]);
printf (" %.3e %+.3ej ",ndat [0][1]);
printf (" %.3e %+.3ej ",ndat [0][2]);
printf ("\n");
```

```
printf (" %.3e %+.3ej ",ndat [1][0]);
printf (" %.3e %+.3ej ",ndat [1][1]);
printf (" %.3e %+.3ej ",ndat [1][2]);
printf ("\n");
printf (" %.3e %+.3ej ",ndat [2][0]);
printf (" %.3e %+.3ej ",ndat [2][1]);
printf (" %.3e %+.3ej ",ndat [2][2]);
printf ("\n");
return(0);
}
/****************************************************************/
// Post invert and multiply 2, 3x3 matrices. Equivalent to 'Answer = a*inv(b)'.
complex post_inv_mul(complex twoin[3][3], complex onein[3][3], complex out[3][3])
{
//      inverse multiply is the function
/*      if b= a*inv(c), then b*c=a       */
complex a[3][3], c[3][3];
complex mid1, a5, mid2, mid3;
complex in1[3][3], in2[3][3], temp[3][3];
int x, y, count;

count = 0;
for (x=0;x<=2;x++)
        {
        for (y=0;y<=2;y++)
                {
                in1[x][y] = onein[x][y];
                in2[x][y] = twoin[x][y];
                }
        }

mid1 = in1[1][2] - in1[1][0]*in1[0][2]/in1[0][0];
a5 = in1[1][1] - in1[1][0]*in1[0][1]/in1[0][0];
a[1][2] = mid1/a5;
mid2 = in1[2][1] - in1[2][0]*in1[0][1]/in1[0][0];
mid3 = in1[2][2] - in1[2][0]*in1[0][2]/in1[0][0];
a[2][2] = mid3 - a[1][2]*mid2;

a[0][0] = a[1][1] = 1;
a[1][0] = a[2][0] = a[2][1] = 0;
a[0][1] = in1[0][1]/in1[0][0];
a[0][2] = in1[0][2]/in1[0][0];

/**************************************************************/
if(a[2][2] == (complex) 0)
        {
        count = 1;
        for (x=0;x<=1;x++)
                {
                for (y=0;y<=2;y++)
```

```
				{
/*swap second and third rows */
				in1[2-x][y] = onein[x+1][y];
				in2[2-x][y] = twoin[x+1][y];
				}
			}
	mid1 = in1[1][2] - in1[1][0]*in1[0][2]/in1[0][0];
	a5 = in1[1][1] - in1[1][0]*in1[0][1]/in1[0][0];
	a[1][2] = mid1/a5;
	mid2 = in1[2][1] - in1[2][0]*in1[0][1]/in1[0][0];
	mid3 = in1[2][2] - in1[2][0]*in1[0][2]/in1[0][0];
	a[2][2] = mid3 - a[1][2]*mid2;

	a[0][0] = a[1][1] = 1;
	a[1][0] = a[2][0] = a[2][1] = 0;
	a[0][1] = in1[0][1]/in1[0][0];
	a[0][2] = in1[0][2]/in1[0][0];
	}
/*************************************************************/
// This is the 'A' matrix sorted
//first row / in1[0][0]
for (x=0; x<=2; x++)
	{
	c[0][x] = in2[0][x]/in1[0][0];
	}
for (x=0; x<=2; x++)
	{
	c[1][x] = (in2[1][x] - in1[1][0]*c[0][x])/a5;
	}
for (x=0; x<=2; x++)
	{
	c[2][x] = (in2[2][x]-in1[2][0]*c[0][x]) - (mid2/a5)*(in2[1][x]-in1[1][0]*in2[0][x]/
in1[0][0]);
	}
//this is the 'C' matrix sorted
for (x=0; x<=2; x++)
	{
	out[x][0] = c[x][0]/a[0][0];
	}
for (x=0; x<=2; x++)
	{
	out[x][1] = (c[x][1] - a[0][1]*out[x][0])/a[1][1];
	}
for (x=0; x<=2; x++)
	{
	out[x][2] = (c[x][2] - a[0][2]*out[x][0] - a[1][2]*out[x][1])/a[2][2];
	}
for (x=0;x<=2;x++)
	{
	for (y=0;y<=2;y++)
```

```
                {
                temp[x][y] = out[x][y];
                }
        }
if ( count != 0)/* swap second and third rows of answer*/
        {
        for (x=0; x<=1; x++)
                {
                for (y=0; y<=2; y++)
                        {
                        out[2-x][y] = temp [x+1][y];
                        }
                }
        }
return(0);
}
/*****************************************************************/
// Pre invert and multiply 2, 3x3 matrices. Equivalent to 'Answer = inv(a)*b'.
complex pre_inv_mul(complex onein[3][3], complex twoin[3][3], complex out[3][3])
{
//      inverse multiply is the function
/*      if b= inv(a)*c, then a*b=c      */
complex a[3][3], c[3][3];
complex mid1, a5, mid2, mid3;
complex in1[3][3], in2[3][3];
int x, y;
for (x=0;x<=2;x++)
        {
        for (y=0;y<=2;y++)
                {
                in1[x][y] = onein[x][y];
                in2[x][y] = twoin[x][y];
                }
        }
mid1 = in1[1][2] - in1[1][0]*in1[0][2]/in1[0][0];
a5 = in1[1][1] - in1[1][0]*in1[0][1]/in1[0][0];
a[1][2] = mid1/a5;
mid2 = in1[2][1] - in1[2][0]*in1[0][1]/in1[0][0];
mid3 = in1[2][2] - in1[2][0]*in1[0][2]/in1[0][0];
a[2][2] = mid3 - a[1][2]*mid2;

a[0][0] = a[1][1] = 1;
a[1][0] = a[2][0] = a[2][1] = 0;
a[0][1] = in1[0][1]/in1[0][0];
a[0][2] = in1[0][2]/in1[0][0];

if(a[2][2] == (complex) 0)
        {
        for (x=0;x<=2;x++)
                {
```

```
        for (y=0;y<=2;y++)
            {
            in1[2-x][y] = onein[x][y];
            in2[2-x][y] = twoin[x][y];
            }
        }
    mid1 = in1[1][2] - in1[1][0]*in1[0][2]/in1[0][0];
    a5 = in1[1][1] - in1[1][0]*in1[0][1]/in1[0][0];
    a[1][2] = mid1/a5;
    mid2 = in1[2][1] - in1[2][0]*in1[0][1]/in1[0][0];
    mid3 = in1[2][2] - in1[2][0]*in1[0][2]/in1[0][0];
    a[2][2] = mid3 - a[1][2]*mid2;

    a[0][0] = a[1][1] = 1;
    a[1][0] = a[2][0] = a[2][1] = 0;
    a[0][1] = in1[0][1]/in1[0][0];
    a[0][2] = in1[0][2]/in1[0][0];
    /*******************************************************************/
    if(a[2][2] == (complex) 0)
    {

    for (x=0;x<=1;x++)
        {
        for (y=0;y<=2;y++)
            {
            in1[1-x][y] = onein[x][y];
            in2[1-x][y] = twoin[x][y];
            }
        }
    mid1 = in1[1][2] - in1[1][0]*in1[0][2]/in1[0][0];
    a5 = in1[1][1] - in1[1][0]*in1[0][1]/in1[0][0];
    a[1][2] = mid1/a5;
    mid2 = in1[2][1] - in1[2][0]*in1[0][1]/in1[0][0];
    mid3 = in1[2][2] - in1[2][0]*in1[0][2]/in1[0][0];
    a[2][2] = mid3 - a[1][2]*mid2;

    a[0][0] = a[1][1] = 1;
    a[1][0] = a[2][0] = a[2][1] = 0;
    a[0][1] = in1[0][1]/in1[0][0];
    a[0][2] = in1[0][2]/in1[0][0];
    /**************************************************/
    }
    }
// This is the 'A' matrix sorted
//first row / [0][0]
for(x=0; x<=2; x++)
    {
c[0][x] = in2[0][x] / in1[0][0];
    }
//second row -(new first row * [1][0]), divided by new [1][1]
```

```
for(x=0; x<=2; x++)
	{
c[1][x] = (in2[1][x] - in1[1][0]*c[0][x])/a5;
	}
//third row -(new first row * [2][0]) then new third row - ( second row * new[2][1])
for(x=0; x<=2; x++)
	{
c[2][x] = (in2[2][x]-in1[2][0]*c[0][x]) - (mid2/a5)*(in2[1][x]-in1[1][0]*in2[0][x]/
in1[0][0]);
	}
//this is the 'C' matrix sorted
for(x=0; x<=2; x++)
	{
out[2][x] = c[2][x]/a[2][2];
	}
for(x=0; x<=2; x++)
	{
out[1][x] = (c[1][x] - a[1][2]*out[2][x]);
	}
for(x=0; x<=2; x++)
	{
out[0][x] = (c[0][x] - a[0][1]*out[1][x] - a[0][2]*out[2][x]);
	}
return(0);
}

/************************************************************/
```

```
// Prepares for calculation of Z looking into a length of three phase cable
// with any termination matrix, calls Zmatrix to calculate impedance
complex Zin_three
        ( int a, double freq, double length, complex Zterm[3][3],
                double main_param[6][50], complex Zmat[50][3][3])
{
FILE *results;
complex Z_matrix[3][3], Y_matrix[3][3];
complex gamma[3][3], gammasq[3][3], gamalen[3][3];
complex y0[3][3], ro[3][3];
complex identity[3][3], Z0[3][3];
int x, y;
double omega = 2*M_PI*freq;

for (x=0;x<=2;x++)
        {
        for (y=0;y<=2;y++)
                {
                identity[x][y] = 0;
                }
        identity[x][x] = 1;
        }
for (x=0; x<=2; x++)
        {
        for (y=0;y<=2;y++)
                {
Z_matrix [x][y]= complex(0, omega*main_param[4][a]);
Y_matrix [x][y]= complex(main_param[6][a], omega*main_param[2][a]);
                }
Z_matrix[x][x]=complex(main_param[0][a], omega*main_param[3][a]);
Y_matrix[x][x]=complex(main_param[5][a],
omega*(main_param[1][a]+2*main_param[2][a]));
        }

mult_mat(Z_matrix, Y_matrix, gammasq);
root_matrix(gammasq[0][0], gammasq[0][1], gamma);
pre_inv_mul(Z_matrix, gamma, y0);
for (x=0;x<=2;x++)
        {
        for (y=0;y<=2;y++)
                {
                gamalen [x][y] = length * gamma[x][y];
                }
        }
refcoef(Zterm, y0, ro);
Zmatrix(y0, ro, gamalen, Zmat[a]);
return(0);
}
```

```
/***************************************************************/
// Prepares for calculation of V looking into a length of three phase cable
// with any termination matrix, calls Vmatrix to calculate voltage
complex Vin_three( int a, double freq, double length, complex Zterm[3][3],
            complex zsrce[3][3], double main_param[6][50],
            complex vsource[3], complex vrec[3])
{
complex Z_matrix[3][3], Y_matrix[3][3];
complex gamma[3][3], gammasq[3][3], gamalen[3][3];
complex y0[3][3], ro[3][3];
complex identity[3][3];
int x, y;
double omega = 2*M_PI*freq;

for (x=0;x<=2;x++)
      {
      for (y=0;y<=2;y++) identity[x][y] = 0;
      identity[x][x] = 1;
      }
for (x=0; x<=2; x++)
      {
      for (y=0;y<=2;y++)
            {
Z_matrix [x][y]= complex(0, omega*main_param[4][a]);
Y_matrix [x][y]= complex(main_param[6][a], omega*main_param[2][a]);
            }
Z_matrix[x][x]=complex(main_param[0][a], omega*main_param[3][a]);
Y_matrix[x][x]=complex(main_param[5][a],
omega*(main_param[1][a]+2*main_param[2][a]));
      }
mult_mat(Z_matrix, Y_matrix, gammasq);
root_matrix(gammasq[0][0], gammasq[0][1], gamma);
pre_inv_mul(Z_matrix, gamma, y0);
for (x=0;x<=2;x++)
      {
      for (y=0;y<=2;y++)
            {
            gamalen [x][y] = length * gamma[x][y];
            }
      }
refcoef(Zterm, y0, ro);
Vmatrix (zsrce, vsource, ro, y0, gamalen, vrec);
return(0);
}
```

```
/*******************************************************/
// Used by Vin_three to calculate voltages using equation 30
complex Vmatrix(complex zsend[3][3], complex vsend[3], complex ro[3][3],
            complex invz0mat[3][3], complex gamalen[3][3],
            complex vrec[3])
{
int x, y;
complex expgamalen[3][3], brack3[3][3], identity[3][3];
complex expgamaexp[3][3];
complex Iplus_egam_ro_egam[3][3], Iminus_egam_ro_egam[3][3];
complex allsec[3][3], firsthalf[3][3];
complex allfirst[3][3], vmult[3][3];
complex Iplusro[3][3], half[3][3];
complex mosttop[3][3], alltop[3][3];

for (x=0;x<=2;x++)
      {
      for (y=0;y<=2;y++)
            {
            identity[x][y] = 0;
            expgamalen[x][y] = exp(-gamalen[x][y]);
            }
      identity [x][x] = 1;
      }
add_mat (identity, ro, Iplusro);
mult_mat (Iplusro, expgamalen, half);
mult_mat(expgamalen, ro, brack3);
mult_mat(brack3, expgamalen, expgamaexp);
sub_mat(identity, expgamaexp, Iminus_egam_ro_egam);
post_inv_mul (half, Iminus_egam_ro_egam, mosttop);
post_inv_mul (mosttop, invz0mat, alltop);
add_mat(identity, expgamaexp, Iplus_egam_ro_egam);
post_inv_mul(Iplus_egam_ro_egam, Iminus_egam_ro_egam, firsthalf);
post_inv_mul(firsthalf, invz0mat, allfirst);
add_mat(zsend, allfirst, allsec);
post_inv_mul(alltop, allsec, vmult);
vrec[0] = vmult[0][0]*vsend[0]+vmult[0][1]*vsend[1]+vmult[0][2]*vsend[2];
vrec[1] = vmult[1][0]*vsend[0]+vmult[1][1]*vsend[1]+vmult[1][2]*vsend[2];
vrec[2] = vmult[2][0]*vsend[0]+vmult[2][1]*vsend[1]+vmult[2][2]*vsend[2];
return(0);
}
```

```
#include <math.h>
#include <dos.h>
#include <stdio.h>
#include <stdlib.h>
#include <complex.h>

int bp,ap;
/*************************************************************/
/* Print the arrays containing all lengths to the screen */
/*************************************************************/
arraytoscreen
      (double spurlength[3][100], double mainlength[100], int feeds,
      complex spurseriesdata [100],
      complex spurparalleldata [100],
      complex mainseriesdata [100],
      complex mainparalleldata [100])
{
double rea, ima;
char buffr[20];
FILE *newfile;
unlink ("phase3.bak");
rename ("phase3.dat","phase3.bak");
newfile = fopen ("phase3.dat","wb");
fprintf (newfile,"Feeds \r%d \r",feeds,"wb");
fprintf (newfile,"Spurlengths \r","wb");
for (bp=0; bp<=2; bp++)
      {
      for (ap=0; ap<=feeds-1; ap++)
            {
            fprintf (newfile,"%e ",spurlength [bp][ap],"wb");
            }
      fputc (0x0d,newfile);
      }

fprintf (newfile,"Mainlengths \r","wb");
for (ap=0;ap<=feeds-1;ap++)
      {
      fprintf (newfile,"%e ",mainlength [ap],"wb");
      }
fputc (0x0d,newfile);

fprintf (newfile,"Spur resistance \r","wb");
for (ap=0;ap<=feeds-1;ap++)
      {
      fprintf (newfile,"%e ", real (spurseriesdata [ap]),"wb");
      }
fputc (0x0d,newfile);

fprintf (newfile,"Spur inductance \r","wb");
for (ap=0;ap<=feeds-1;ap++)
```

```
        {
        fprintf (newfile,"%e ", imag (spurseriesdata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Spur admittance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", real (spurparalleldata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Spur capacitance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", imag (spurparalleldata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Main resistance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", real (mainseriesdata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Main inductance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", imag (mainseriesdata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Main admittance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", real (mainparalleldata [ap]),"wb");
        }
    fputc (0x0d,newfile);

    fprintf (newfile,"Main capacitance \r","wb");
    for (ap=0;ap<=feeds-1;ap++)
        {
        fprintf (newfile,"%e ", imag (mainparalleldata [ap]),"wb");
        }
    fputc (0x0d,newfile);
    fclose (newfile);
    return(0);
    }
```